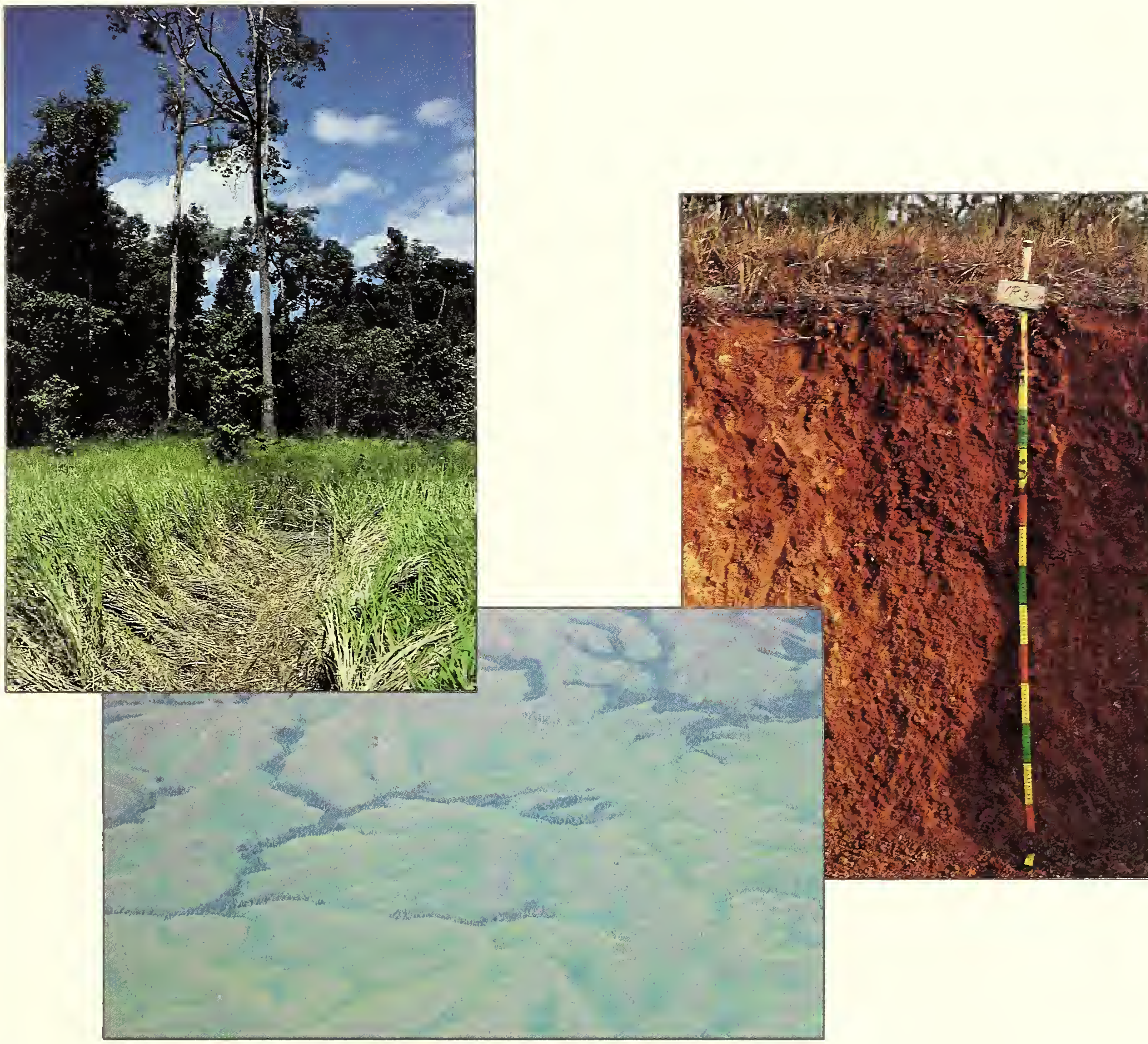
Proceedings of a

Symposium on Low Activity Clay (LAC) Soils

Las Vegas, Nevada
November 26–30, 1984



SMSS Technical Monograph No. 14

For more information on the SOIL MANAGEMENT SUPPORT SERVICES, contact your USAID country mission or write to:

Dr. Richard Arnold
Director, Soils
Soil Conservation Service
P.O. Box 2890
Washington, D.C. 20523
Tel: (202) 382-1820

Dr. Hari Eswaran
Program Leader, SMSS
P.O. Box 2890
Washington, D.C. 20523
Tel: (202) 475-5330

Dr. Raymond Meyer
Project Monitor, SMSS
S&T/AGR/RNR
Agency for International Development
Washington, D.C. 20523
Tel: (703) 235-8993

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The papers included in this monograph were presented at a symposium organized by the Soil Science Society of America during the Annual Meeting of the Agronomy Society of America. The Soil Management Support Services (SMSS) wishes to acknowledge with thanks for the release of the papers to SMSS to enable it to publish this monograph.

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FOREWORD

Since 1975, and even prior to the publication of Soil Taxonomy, this system of soil classification was used in many countries of the world. The final draft had already received international distribution by 1970, although the monograph was actually published in 1975. As a result, since 1975, the Soil Conservation Service (SCS) of the U.S. Department of Agriculture received many comments on its application particularly in the intertropical areas. One problem area which emerged was that of low activity clays (LAC) soils, and SCS requested Dr. Frank Moormann, who then worked for the International Institute for Tropical Agriculture in Nigeria and currently is at University of Utrecht, Netherland, to initiate discussions on this subject and make proposals for modifications to Soil Taxonomy.

Dr. Moormann formed a "committee" which was later formalized and called the International Committee on Low Activity Clays (ICOMLAC), and he initiated the Circular Letters to communicate with the cooperators from different parts of the world. The Agency for International Development (AID) recognized this network of international soil scientists and, in 1976, awarded a grant to the University of Puerto Rico for organizing a workshop to discuss the committee affairs. The first workshop held in Brazil in 1976 was the forerunner of the International Soil Classification Workshops organized by the Soil Management Support Services (SMSS) which was created by AID and implemented by SCS in 1979.

By about 1983, ICOMLAC was far advanced in its discussions and a draft proposal had been developed for discussions. SMSS considered it an opportune moment to organize a symposium in conjunction with the annual meeting of the Agronomy Society of America at Las Vegas, Nevada during 25-30 November 1984. The purpose of the symposium was to present the ICOMLAC Proposal to a wider audience and to determine the state-of-the-knowledge of the LAC soils. Specialists in various fields were invited to present papers and these are included in this proceedings.

ICOMLAC work continued after this meeting and on August 1986, the final proposal was accepted by SCS and published as a National Soil Taxonomy handbook notice. The Prologue to this proceeding includes the excerpts from the Handbook and is included because there were changes to the definition and concept since 1984.

This Proceeding is a tribute to Dr. Frank Moormann and all soil scientists around the world, who toiled for more than ten years to discuss, evaluate and finally develop the ICOMLAC Proposal. The Soil Management Support Services wishes to take this opportunity to thank each and everyone of you for your contributions.

Hari Eswaran
October 1986

PROLOGUE

The International Committee on Low Activity Clay soils (ICOMLAC), chaired by Dr. Frank Moormann from University of Utrecht, The Netherlands, was created in 1975 by the Soil Conservation Service (SCS) to address the classification of low activity Alfisols and Ultisols. The Committee, which was open to all interested personnel both nationally and internationally, operated through Circular Letters which have been excerpted and published (Moormann, 1985). This publication provides the background material for the amendments given here. The work of the committee was also facilitated by the organization of Soil Classification Workshops funded by the Agency for International Development and organized by the Soil Management Support Services (SMSS) and the University of Puerto Rico. The proceedings of these workshops (Camargo and Beinroth 1978, Beinroth and Panichapong 1979, Beinroth *et al*. 1983) also provide background materials for the rationale to the new concepts incorporated in these amendments.

The introduction of the kandic horizon reduces many of the difficulties encountered in appplication of the definition of the argillic horizon. The new taxa provides a more logical place in *Soil Taxonomy* for many soils in the intertropical areas of the world that have properties transitional to Oxisols. It is believed that introduction of these taxa will enhance the quality of *Soil Taxonomy* in its function of making and interpreting soil surveys.

The proposals of ICOMLAC have been coordinated with the discussions of the other international soil classification committees, particularly the International Committee on Oxisols (ICOMOX). The final proposal of ICOMLAC was circulated by SCS to national and international cooperators for testing, review, and comments.

The following changes in *Soil Taxonomy* will accommodate this amendment.

Page 27, second column, preceding Agric horizon, add: "KANDIC HORIZON".

Genesis

A kandic horizon is a subsurface horizon with a significantly higher percentage of clay than the overlying horizon or horizons and has a CEC $\leq$16 meq per 100 g clay (by 1N NH_4OAc pH 7) and an ECEC $\leq$12 meq per 100 g clay (sum

of bases extracted with 1N NH_4OAc pH 7 plus 1N KCl extractable Al). The clay size fraction is composed predominantly of 1:1 layer silicate clays, mainly kaolinite, with varying amounts of oxy-hydroxides of iron and aluminum. Clay skins may or may not be present. (The percentage of clay is measured by the pipette method of 2.5 times 15-bar water, whichever is higher but not more than 100.)

The textural differentiation in pedons with kandic horizons may result from one or more processes acting simultaneously or sequentially, affecting surface horizons, subsurface horizons, or both. These processes are not all clearly understood, although the most important ones can be summarized as follows.

1. Clay eluviation and illuviation

In some soils it is often difficult to find clear evidence, even by micromorphological analysis, that the higher clay content in the B horizon is a result of accumulation by illuviation of layer silicate clays. Specifically, clay skins (cutans) may be completely absent, or they may be present only at depths below the control section used in classification. In other soils, clay skins may have been destroyed by biological activity or pedoturbation processes. High concentrations and strong activity of soil fauna in soils of tropical and subtropical areas, where kandic horizons are common, may cause the partial or total disappearnace of clay skins over time and to a considerable depth.

Many of the soils with kandic horizons, that have probably formed by illuvial processes, occur on stable geomorphic surfaces. On stable surfaces, the illuviation process may no longer be operative, or at least acting so slowly that mixing by soil organisms is more rapid than the formation of clay skins. Under these conditions, clay skins may be found in some pedons but not in other nearby pedons which otherwise have similar morphology. Even within the same horizon of a single pedon, some peds may have clay skins while others do not.

2. Clay destruction in the epipedon

Weathering of layer silicates may lead to a relative loss of clay in soils. The loss is usually greatest in the upper horizons where weathering processes are most intense. Elimination of bases and some silica is enhanced by high surface soil temperatures in well-drained soils with high rates of leaching. Because this process affects surface horizons more than subsoil horizons, a vertical textural differentiation may result. This may also explain the absence

of clay skins in the lower horizons of highly weathered soils on old stable surfaces. A related process which occurs in surface horizons that are periodically wet may also result in similar textural differentiation.

3. Selective erosion

Raindrop splash and subsequent surface soil erosion cause the smallest soil particles to be moved farther downslope than larger particles. Eventually, part of the fine fraction may be eliminated from the surface layer of sloping soils, leaving a coarser textured surface layer. The speed of this process depends on many factors, but in climates with highly erosive rains, or on soils with little plant cover, it may be very rapid. The surficial movement of clay downslope seems to be widespread and selective erosion probably is a major process leading to textural differentiation. The process appears to be enhanced by periodic fire or intermittent cultivation as practiced for thousands of years of shifting cultivation in areas where these soils occur.

4. Sedimentation of coarse-textured surface materials

Lithologic discontinuities are probable on stable landscapes in many intertropical areas. In many of the soils of these areas, the surface layer is coarser textured than the subsoil, but due to the fact that all the soil material is highly weathered, stratification is not evident. If the finer textured subsoil fulfills the requirements of the kandic horizon and the surface layer is not composed of fine strata of recent material, the subsoil horizon is classified as a kandic horizon.

Significance to Soil Classification

The kandic horizon provides a basis for differentiation among soils with clay accumulation in the subsoil. The argillic horizon alone does not provide an adequate diagnostic criterion to differentiate all Ultisols and Alfisols from Oxisols and Inceptisols. The kandic horizon is a diagnostic horizon that separates Ultisols and Alfisols in which the clay fraction has clay minerals with low CEC, comparable to Oxisols, from Ultisols and Alfisols with clay minerals of high CEC. Textural differentiation in most low activity clay (LAC) soils by itself is believed to be sufficiently important for the understanding of soil development and use, and should be recognized at a high level of the

classification system. However, in soils with clayey surface textures, the textural differentiation loses much of its significance.

Most low activity clay soils that have, after mixing the upper 18 cm of the soil, more than 40 percent clay in the surface horizon will be Oxisols (after the ICOMOX Proposal is approved); although a few soils with LAC and necessary clay increase for an argillic or kandic horizon, but have significant amounts of weatherable minerals, will remain kandic Ultisols or Alfisols. It is also possible that a few with a more gradual clay increase and with a higher weatherable mineral content in the coarser fractions could be Inceptisols or pale Alfisols or Ultisols.

The presence of a kandic horizon indicates a high degree of weathering of the mineral soil material such as that in soils on old surfaces where weathering has taken place under warm climatic conditions with moderate to high precipitation. The high degree of weathering is reflected by a dominance of 1:1 layer silicate clays and oxy-hydroxides of iron and aluminum although small amounts of 2:1 layer silicate clays may also be present. There is a general absence of short-range order minerals such as allophane or immogolite. The composition of the 0.02 to 0.2 mm fraction does not always reflect the same degree of weathering, especially in soils formed in weathering products of crystalline rocks. Thus, no weatherable mineral content is specified in the kandic horizon definition.

Identification

The kandic horizon is a vertically continuous subsurface horizon (not composed of lamellae) with a significantly finer texture than the overlying horizon or horizons. It may underlie an ochric, umbric, anthropic, or mollic epipedon. The upper boundary normally is clear or gradual, although it may be abrupt, but is never diffuse. The increase in clay content is reached within a vertical distance of 15 cm or less.

The top of the kandic horizon is within one of the following depths.

A. If the particle-size class throughout the upper 100 cm is sandy, the upper boundary is at a depth between 100 cm and 200 cm from the soil surface in most of the pedon.

B. If the clay content of the surface horizon is less than 20 percent and the particle-size class (of part or all of the upper 100 cm) is finer

than sandy, the upper boundary is at a depth of less than 125 cm from the soil surface.

C. If the clay content of the surface horizon is 20 percent or more, the upper boundary is at a depth of less than 100 cm from the mineral soil surface.

It is intended to exclude from the kandic horizon textures coarser than loamy very fine sand. The presence or absence of clay skins, by field examination or cutans in thin sections, is not a differentiating characteristic for kandic horizons.

Other field characteristics of kandic horizons are not normally diagnostic, since these horizons may have properties of the argillic, the cambic, or the oxic horizon. Some soils with kandic horizons resemble those with argillic horizons in that they have a well-developed subangular blocky structure, while bleached grains of sand and silt may be present in the overlying coarser textured horizon(s). The ratio of fine clay (particles smaller than 0.2 um) to total clay may be larger in the kandic horizon than in the overlying coarser horizon(s) but is not diagnostic.

Other kandic horizons have one or more properties of the oxic horizon and they would be called an oxic horizon except for the distinct clay content increase at the upper boundary. This rationale is comparable to pedons dominated by more active clays where an argillic horizon occurs that would have been called a cambic horizon except for the clay content increase at the upper boundary.

A kandic horizon is not overlain by layers more than 30 cm thick which show fine stratification and/or have organic carbon contents which decrease irregularly with depth unless it is a buried horizon. The kandic horizon also does not show fine stratification and/or have organic carbon contents which decrease irregularly with depth.

Summary of Properties

The kandic horizon:

1. Is a vertically continuous subsurface horizon and has, starting at the point where the clay increase requirements are met, a CEC of $\leq$16 meq per 100 g clay (by 1N NH_4OAc pH 7) and an ECEC $\leq$12 meq per 100 g clay (sum of bases extracted with 1N NH_4OAc pH 7 plus 1N KCl extractable Al) in at least the major part of the horizon.

2. Has a thickness of at least 30 cm, or if a lithic, paralithic, or petroferric contact occurs within 50 cm of the soil surface, then the thickness of the kandic horizon is at least 60 percent of the vertical distance between 18 cm and the contact but at least 15 cm thick.
3. Has a texture of loamy very fine sand or finer.
4. Underlies a coarser textured surface horizon. The minimum thickness of the surface horizon is 18 cm after mixing, or 5 cm if the textural transition to the kandic horizon is abrupt and if there is no lithic, paralithic, or petroferric contact within 50 cm.
5. Has more total clay than the overlying coarser textured surface horizon and the increased clay content is reached within a vertical distance of 15 cm or less as follows.
   a) If the surface horizon as defined above has less than 20 percent total clay, the kandic horizon begins where some subhorizon contains at least 4 percent more clay absolute than the overlying horizon.
   b) If the surface horizon as defined above has 20 to 40 percent total clay, the kandic horizon begins where some subhorizon has at least 1.2 times more clay than the overlying horizon.
   c) If the surface horizon as defined above has more than 40 percent total clay, the kandic horizon begins where some subhorizon has at least 8 percent more clay absolute than the overlying horizon.

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CLASSIFICATION OF ALFISOLS AND ULTISOLS WITH LOW ACTIVITY CLAYS

F.R. Moormann[1]

Introduction

Post-World War II soil research and extensive soil surveys in tropical and subtropical regions have considerably increased our knowledge of the soils of such areas. Moormann and van Wambeke (1978) indicate that in the overall tropical rainy areas an estimated 70 percent of the soils are highly weathered. In such soils the clay fraction is dominated by a 1:1 layer lattice silicate clays, mainly kaolinite, and by oxides and hydrous oxides of iron, with common occurrences of gibbsite. Clays with such a composition have been given the generic name "low activity clays" pertaining to the low CEC (pH 7) of the clay fraction. Outside the tropical zone, proper LAC dominated soils extend somewhat to the adjacent humid mesothermal zone (Flach and Tavernier 1978). In the southeastern United States and in southeast China, in particular, strongly weathered soils are common. Nevertheless, the proportion of LAC-dominated soils is considerably lower than in the Tropics.

Present Place of LAC-dominated Taxa in *Soil Taxonomy* (Soil Survey Staff 1975)

The dominance of low activity clays is used as a diagnostic criterion at several levels in *Soil Taxonomy*.

Order level. Low CEC is implied in the definition of those Oxisols which have an oxic horizon, since a key attribute of that horizon is a low CEC per 100 g clay by NH_4OAc (CEC 7) or a low ECEC (bases extractable with NH_4OAc + Al extractable with 1N KCl) per 100 g clay.

Subgroup level. Low CEC is diagnostic in a number of taxa of Alfisols, Ultisols, Mollisols and Inceptisols. In the present definition, such LAC subgroups (oxic, orthoxic, ustoxic) have a CEC 7 of less than 24 meq/100 g clay.

Family level. Many of the soils with a ferritic, gibbsitic, or oxidic mineralogy class are LAC soils. Also, the clayey or clayey-skeletal soils with a kaolinitic mineralogy class often belong to this category. However, no LAC mineralogy is distinguished in soils with a particle-size class coarser than clayey or clayey-skeletal.

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[1] ICOMLAC Chairman and Professor of Soil Science at Utrecht University.

The subgroup is the highest level of generalization at which LAC Alfisols and Ultisols are distinguished and named in the present version of Soil Taxonomy. Of the 37 great groups of Alfisols, 4 have a LAC subgroups (oxic), while 6 out of 24 Ultisol great groups have one or more LAC subgroups. Smith, Sys, and Van Wambeke (1975) proposed additional oxic subgroups for Paleudults and Paleustults, based on the interpretation of data from Zaire (Sys 1972). From studies elsewhere in the intertropical zone (e.g., Theng 1980, Greenland 1981) it has become clear that many additional LAC taxa of Alfisols and Ultisols would be needed.

Rationale for Reclassifying LAC Alfisols and Ultisols

Many workers involved in the taxonomic classification of soils in the tropics consider the 1975 placement of LAC Alfisols and Ultisols unsatisfactory, and the level of placement available in the current version of Soil Taxonomy being too low. In order to remedy this situation, the Soil Conservation Service of the USDA appointed in 1975 an international committee (ICOMLAC) to make proposals for upgrading the LAC taxa of Alfisols and Ultisols. It is intended that this operation will eventually also cover the LAC subgroup Mollisols and Inceptisols.

Reasons to upgrade the LAC taxa include the following.

Genetic aspects. The LAC property reflects to a large extent the "state of weathering" of the mineral portion of the pedon. Dominance of the clay fraction of 1:1 lattice layer clays and oxy-hydroxides of Fe and Al indicate advanced weathering. It should be pointed out, however, that this strong weathering is not necessarily always reflected in the coarser fraction, which may contain readily weatherable minerals (Juo 1980, Hughes 1981).

Taxonomic aspects. In the present oxic subgroups of Alfisols and Ultisols, strongly divergent pedons are grouped in the same taxon. No provision is made for further differentiation at a level above the family or even above the series. This stands in no relation to the possibility of subdivision of better known taxa, for example, in the temperate region of the United States.

Management-related aspects. LAC soils, like Oxisols, differ greatly in terms of management-related properties from soils with appreciable content of higher activity clays of the 2:1 lattice layer type. Chemically, the nutrient status is well below that of high activity clay soils (HAC) with

comparable clay content, which may lead to rapid depletion, acidification, and so on (Fox 1980). Physically, a main limitation of LAC soils is a lower effective water-holding capacity, leading to drought stress in cultivated plants after relatively short periods without rain (Uehara and Keng 1975, Lal 1980).

Correlation aspects. Other genetic and taxonomic systems of soil classification, such as the French system (CPCS 1967) have used the pedogenetic or inherited degree of strong weathering at a high categorical level. The fact that in Soil Taxonomy this was not done, at least in the Alfisol and Ultisol orders, hampers the comparison between systems. In Soil Taxonomy, the presence of the argillic horizon is recognized as a diagnostic property at the highest (Order) level, while the degree of weathering (viz, the clay mineralogy) is used at the lowest of the four pedogenetic categories (i.e., Subgroup). In the CPCS system, the opposite is true. The equivalents of Oxisols and the oxic subgroups of various other orders mainly go into one "classe," that of the Ferrallitic soils, while the criteria used in Soil Taxonomy for defining Alfisols and Ultisols can be partly found at lower levels of generalization.

By upgrading the level at which LAC propeties are recognized, interpretation in terms of Soil Taxonomy of maps based on the CPCS (1967) or the INEAC classification system (Tavernier and Sys 1965) is considerably simplified.

Level of Classification of LAC-dominated Alfisols and Ultisols

All three levels above the present one (subgroup) have been considered by ICOMLAC and collaborators, resulting in a final proposal which is now being tested. A first possibility was to distinguish the LAC properties at the order level by introducing a new order or, alternatively, by changing the definition of the present order of Oxisols. This would have led to a virtual rewriting of important portions of Soil Taxonomy. The concept of the present orders of Alfisols and Ultisols is of soils with considerable translocated phyllosilicate clays, whereby Alfisols are high and Ultisols are low in bases.

The concept of the present Order Oxisols is of intensive weathered soils without clear signs of translocated phyllosilicate clays in the diagnostic part of the solum. Base saturation is not a property used for defining the Order. Elevating the LAC Alfisols and Ultisols to the level of a new order would create a grouping based on both concepts. Incorporating the LAC Alfisols and

Ultisols into the Order Oxisols would again imply the mixing of the two concepts and would strongly affect the present structure of Soil Taxonomy. The second possibility was to distinguish new LAC taxa at the suborder level.

Although the differentiating criteria for the suborders vary, those used for Alfisols and Ultisols virtually excluded the introduction of the LAC characteristics at that level. Moreover, a major drawback would be the doubling of the number of suborders in Ultisols (from 5 to 10) and the sharp increase in Alfisol suborders (from 5 to 8). Therefore, the decision was made to differentiate the LAC taxa at the great group level for most LAC pedons of Alfisols and Ultisols. Separation at this categorical level is indicated because in order to define soils at the great group level, the nature and composition of all horizons are considered collectively and the LAC property is one that extends to all horizons of the solum.

The nomenclature proposed for the LAC taxa is based on the predominance of 1:1 layer lattice clays (kandites) in the clay mineralogical suite of the LAC pedons. In analogy to the present separation between great groups with a deep argillic horizon and those with a shallower one, two LAC taxa are introduced in many of the present suborders for which the prefixes "kandi" and "kanhapl" are used, respectively, for deep and shallower pedons.

The LAC properties were given a high ranking in the keys of the great groups; hence most LAC pedons will key out as kandi or kanhapl great groups. Some properties were given a higher ranking in the naming of great groups, for example, the presence of plinthite, of a natric horizon, of a fragipan, of a sombric horizon, and a few others. The LAC property, if present, would be recognized at the subgroup level. However, with the exception of the "plinth" great groups and of the Sombrihumults, no, or only occasional LAC subgroups are required.

Diagnosis of LAC Alfisols and Ultisols

The incorporation of LAC taxa in the current version of Soil Taxonomy requires some major and several minor reconsiderations of diagnostic horizons and properties. Introduction of new or revised parameters for use in classifying taxa frequently brings about far-reaching changes in the existing structure of the classification. In revising Soil Taxonomy for incorporating th LAC Alfisols and Ultisols, preference was given to such changes which least affect the existing classes.

The most important diagnostic changes proposed for classifying LAC Alfisols and Ultisols pertain to charge properties (CEC), genetic horizons, weatherable minerals, and soil temperature regime.

Charge properties of clay fraction

For determination of the composition of soil clays, various techniques are available. It might, therefore, appear logical that the definition of "Low Activity Clays" be based on the actual composition of these clays; that is, mainly kaolinite (kandite group) with variable admixtures of Fe and Al oxides and hydrous oxides. For several reasons, however, the operational definition of the term LAC is not based on the measured mineralogy of the clay fraction. The quantification of such measurements is as yet very difficult, time-consuming, and costly. Moreover, in only a few laboratories of the tropical world, do facilities exist for such routine determination of the clay mineralogy composition, which would be necessary for soil survey and taxonomic classification purposes. Instead of the mineralogical assemblage, we therefore use physicochemical properties of the clay fraction and, more specifically, the cation-exchange capacity as a measure for clay activity. Difficulties in the use of CEC as a diagnostic property are considerable. In low activity clays, values per unit clay are low and, hence, small errors in determination may result in considerable differences in analytical results. Nevertheless, CEC seems to be, at present, the only parameter which can be used routinely to distinguish LAC Alfisols and Ultisols from those with higher clay activity. The following two methods are proposed to be used as alternates or in combination for determining the critical CEC.

- CEC 7, by NH_4OAc at pH 7, and/or
- ECEC, sum of bases extracted with 1N NH_4OAc plus 1N KCl extracted Al at soil pH.

Critical values are now being tested for:

- CEC 7 less than 16 meq per 100 g clay, and/or
- ECEC less than 12 meq per 100 g clay.

Below these values, the clay fraction is defined as a low activity clay. No corrections are made for the CEC of organic matter present; instead, the control section for determing the critical CEC is chosen such that it includes major portions of horizons in which the content of organic matter is low or even negligible.

Diagnostic subsurface horizon--the Kandic horizon

The 1975 edition of Soil Taxonomy requires Alfisols and Ultisols to have an argillic horizon. An argillic horizon is stated to contain illuvial layer-lattice clays. This horizon requires a specific clay increase compared to an overlaying eluvial horizon or the presence of clay skins (bridges), or both (Soil Taxonomy 1975, p. 27, Summary of Properties).

This concept of the argillic horizon and its use in Soil Taxonomy has given rise to severe controversies (Isbell 1980), particularly in LAC Alfisols and Ultisols where clay skins or oriented clay-bridges cannot irrefutably be identified in the field and/or by microscopic study of thin sections. In many LAC pedons, such supposed argillic horizons have most of the characteristics of an oxic horizon (Soil Taxononmy, p. 36-41), and such pedons would be classified as Oxisols were it not that a clear, presumably nonsedimentary increase of clay content is found.

Similar difficulties are met in the distinction of certain LAC Alfisols and Ultisols from Inceptisols dominated by low activity clays. These cases are, however, much less frequent. To help solve the controversy in recognizing argillic horizons in Alfisols and Ultisols, a new diagnostic horizon, the kandic horizon was introduce (Moormann and Buol 1981). A kandic horizon is a subsurface horizon with a significantly higher percentage of clay than the overlying horizon or horizons, that has ECEC of 12 meq or less per 100 g clay and/or a CEC of less than 16 meq per 100 g clay (by NH_4OAc pH 7). The clay size fraction is composed predominantly of 1:1 layer lattice silicate clays, mainly kaolinite, with varying amounts of oxy-hydroxides of Fe and Al. The textural differentiation in pedons with kandic horizons may result from one or more processes acting simultaneously or sequentially, affecting surface horizons, subsurface horizons, or both.

The pathways of formation of a kandic horizon include:

- clay illuviation with subsequent destruction of clay skins;
- clay destruction in the upper horizons;
- selective erosion of finer soil particles from the surface horizon; and
- sedimentation of coarse texture surface materials.

Summary of Properties of Kandic Horizon

The kandic horizon is a vertically continuous subsurface horizon which has a thickness of 30 cm or more from the point where clay increase requirements are met, and has ECEC of less than 12 meq per 100 g clay, or CEC 7 or less than 16 meq per 100 g clay.

The kandic horizon is a vertically continuous subsurface horizon which has a thickness of 30 cm or more from the point where the clay increase requirements are met, and has ECEC of less than 12 meq per 100 g clay or CEC 7 or less than 16 meq per 100 g clay.

The kandic horizon underlies a coarser textured surface horizon. The minimum thickness of the surface horizon is 18 cm after mixing, or 5 cm when the textural transition to the kandic horizon is abrupt and when there is no lithic, paralithic, or petroferric contact within 33 cm.

The kandic horizon contains more total clay than the overlying coarser textured surface horizon and the increased clay content is reached within a vertical distance of 15 cm or less as follows.

- If the surface horizon has less than 20 percent total clay, the kandic horizons begins where some subhorizon contains at least 4 percent more clay absolute than the overlying horizon.
- If the surface horizon has 20 to 40 percent total clay, the kandic horizon begins where some subhorizon has at least 1.2 times more clay than the overlying horizon.
- If the surface horizon has more than 40 percent total clay, the kandic horizon begins where some subhorizon has at least 8 percent more clay absolute than the overlying horizon.

The kandic horizon has a texture of loamy fine sand or finer. Its thickness is at least 30 cm; or if lithic, paralithic, or petroferric contact occurs within 30 to 70 cm of the mineral soil surface, then the thickness of the kandic horizon should be at least 60 percent of the vertical distance betweeen 18 cm and the contact.

Weatherable minerals

In Soil Taxonomy (1975), the absence of weatherable minerals in the 20 to 200 micron fraction is used as a diagnostic criterion in the definitions of Paleaquults and Paleudults. Logically, the LAC taxa with properties similar to these two great groups might be expected to have low or negligible contents of weatherable minerals as well.

Studies, among others in West Africa (Greenland 1981), made it clear that the content of weatherable minerals in LAC Alfisols and Ultisols often varies independently from the highly weathered nature of the clay in these pedons. It was found, therefore, that the content of weatherable minerals cannot be used as a diagnostic property for LAC taxa at the Great Group level.

Soil temperature regime

In the current version of Soil Taxonomy, the soil temperature regime is used to define "trop" Great Groups of Aqualfs, Udalf, Aquults, Humults, and Udults. The rationale was that in soils with an aquic or udic moisture regime and an uninterrupted high soil temperature (isomesic or warmer) plant growth and crop production can be continuous throughout the year. This was in opposition to taxa with a nonisotemperature regime or with a dry period such as in the ustic and xeric taxa. It was a point of discussion of whether, in LAC taxa which straddle the isotemperature and nonisotemperature regimes, the equivalent of the "trop" separation should be introduced. This was not done. Omitting such a separation in the LAC taxa causes the "trop" great groups to become virtually redundant. As a consequence, these great groups were dropped from the proposed reclassification of Alfisols and Ultisols.

The LAC Taxa

Kandic and Kanhaplo Great Groups

In most of the present suborders of Alfisols and Ultisols, Pale-Great Groups are distinguished. Essentially, these Pale taxa are defined on the relatively great thickness of the argillic horizon or, in some cases, on the absence of a transition to a C horizon within a depth of 180 cm. The great groups which key out after the Pale-Great Group have by definition a thinner solum, the transition to an underlying horizon or layer being found at less than 150 cm depth.

Then, deciding upon the taxa to be introduced for LAC-dominated Alfisols and Ultisols, it was found that introduction of a similar separation between deep and shallow LAC taxa is necessary. Hence, in most suborders of Alfisols and Ultisols, the following two LAC taxa are distinguished.

1) The kandi taxa that do not have a lithic, paralithic, or petroferric contact within 1.5 m of the soil surface and that have clay distribution such that the percentage of clay does not decrease from its minimum amount by as much as 20 percent within 1.5 m of the surface.

2) The kanhapl-taxa that do not meet these requirements because the diagnostic argillic or kandic horizon is thinner. Kandi- and

kanhapl-Great Groups are recognized in the following suborders: Ustalfs, Udalfs, Aquults, Humults, Udults, and Ustults. In Aqualfs, no subdivision was made between the shallow and deep LAC taxa. The existence of LAC soils in this Suborder has not been definitely established.

Limits between LAC taxa and other soils

To distinguish LAC Alfisols and Ultisols from Oxisols, the LAC taxa must have either:

1) a clay content of less than 40 percent in the surface 18 cm after mixing and an argillic or kandic horizon, or

2) a clay content of 40 percent or more in the surface 18 cm after mixing and an argillic horizon with clear clay skins, both discernible in the field and in thin sections.

The second distinction rests on the presence of clear clay skins in the argillic horizon. If such skins are doubtful or also if they occur in the lowest portion of the argillic horizon only, it is proposed that the pedon in question be classified as an Oxisol.

To distinguish the LAC Alfisols and Ultisols from LAC Inceptisols, the LAC Inceptisols should not have a kandic or argillic horizon, irrespective of the texture of the upper horizons. Moreover, the LAC Inceptisols should have more than 10 percent weatherable minerals.

To distinguish LAC Alfisols and Ultisols from other Alfisols and Ultisols, the LAC taxa must have a CEC 7 that is less than 16 meq per 100 g clay or have ECEC that is less than 12 meq per 100 g clay in: (1) the major part of the upper 100 cm of the argillic or kandic horizon for kandi taxa, or (2) the major part of the total argillic or kandic horizon for kanhapl taxa. In great groups which key out before the kandi taxa, the distinction between LAC soils and others remains at the subgroup levels. In the 1975 edition of Soil Taxonomy, only two of these great groups have a LAC (oxic) subgroup, the Plinthaquults and the Sombrihumults.

The place of LAC taxa in Keys

Prior to official establishment of the kandi and kanhapl taxa, a proposal for the reclassification of Ultisols and Alfisols with low activity clay soils is being tested internationally. The proposed listing of suborders and great groups of Alfisols and Ultisols with LAC taxa follows.

HA AQUALFS

HAA Plintaqualfs	HAF Glossaqualfs
HAB Natraqualfs	HAG Albaqualfs
HAC Duraqulafs	HAH Umbraqualfs
HAD Fragiaqualfs	HAI Ochraqualfs
HAE Kandiaqualfs	

HC USTALFS

HCA Durustalfs
HCB Plinthustalfs
HCC Nastrustalfs
HCD Kandiustalfs
HCE Kanphaplustal
HCF Paleustalfs
HCG Rhodustalfs
HCH Haplustalfs

HE UDALFS

HEA Argudalfs
HEB Natrudalfs
HEC Ferrudalfs
HED Glossudalfs
HEE Fraglossudalffs
HEF Fragiudalfs
HEG Kandiudalfs
HEH Kanhapludalfs
HEI Paleudalfs
HEJ Rhodudalfs
HEK Hapludalfs

FA AQUULTS

FAA Plinthaquults
FAB Fragiaquults
FAC Albaquults
FAD Kandiaquults
FAF Paleaquults
FAG Ochraquults

FB HUMULTS

FBA Sombrihumults
FBB Plinthohumults
FBC Kandihumults
FBD Kanhaplohumults
FBE Haplohumults

FC UDULTS

FCA Plinthudults
FCB Fragidults
FCC Kandiudults
FCD Kanhapludults
FCE Paleudults
FCF Rhodudults
FCG Hapludults

FD USTULTS

FDA Plinthustults
FDB Kandiustults
FDC Kanhaplusults
FDD Paleustults
FDE Rhodulstults
FDF Haplustults

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LAC-OXISOL INTERFACE

S.W. Buol[1]

Abstract

Soils that have both the mineralogical and cation-exchange properties defined for Oxisols, and the clay content increase with depth defined for an argillic horizon are discussed as LAC-Oxisol interface soils. In 1960, these soils were considered Oxisols, but in 1975 they were considered Ultisols or Alfisols, if the presence of an argillic horizon was determined. Clay skins and other accessory features of the argillic horizon are weakly developed or even entirely lacking in many LAC-Oxisol pedons. Slow rates of lessivage, pedoturbation, and alternative pedogenic scenarios are discussed that may lead to argillic horizon morphology in materials of oxic horizon composition. Proposals currently being considered to facilitate the classification of these soils are presented. Rationale for the proposed changes is discussed.

Introduction

"Perfect scientific classification is first possible when one knows everything concerning the classified natural objects" (Kubiena 1948). If one axiomatically accepts Kubiena's statement, then there is a good chance the perfect soil classification system probably has not yet been attained. The uneven availability of information about and comprehension of the genesis of soils in the world was a problem during the development Soil Taxonomy (Soil Survey Staff 1975). It is still a problem.

When the 7th Approximation (Soil Survey Staff 1960) was prepared, the lack of information concerning Oxisols was widely acknowledged. There was also insufficient information on soils mineralogically similar to Oxisols. In the last 25 years, many LAC-Oxisol interface pedons have been characterized, thus, providing the basis for criteria to define the taxonomic categories. However, experience in testing the proposed criteria in detailed soil surveys using soil series defined according to the National Cooperative Soil Survey as practiced in the United States is still not available. The associated experience of developing the interpretive information for map units of these kinds of soils is likewise not commonly available. Because the vast majority of soils encompassed by the LAC-Oxisol interface are in countries of diverse social and economic structures, the opportunities for practical interpretive testing of taxonomic or map units either is, or will remain, a severe handicap to their understanding.

[1] Professor of Soil Science, Department of Soil Science, North Carolina State University, Raleigh, NC 27695-7619.

The objectives of this paper are to: (1) briefly examine the historical development of the classification criteria in LAC-Oxisol soils; (2) present data that have resulted in presently proposed changes of existing criteria; and (3) explain and illustrate some of the problems that exist with respect to the acceptance of classification criteria.

What is the LAC-Oxisol Interface?

> The Oxisols include the soils that, in recent years, have been called Latosols, and many, if not most, of those have been called Ground-Water Laterite soils. Earlier, they were called Laterite soils. All soils that have oxic horizons are included in the order. Their epipedons may be umbic or ochric, histic, and perhaps mollic. They may have argillic horizons. (Soil Survey Staff 1960)

> Oxisols are mineral soils that
> 1. Meet one of these two requirements:
>   a. Have an oxic horizon at some depth within 2 m of the soil surface; or
>   b. Have plinthite that forms a continuous phase within 30 cm of the soil surface and the soil is saturated with water within this depth at some time of year in most years; and
> 2. Do not have a spodic horizon or an argillic horizon that overlies the oxic horizon. (Soil Survey Staff 1975)

At the risk of over simplification, those pedons that qualified for Oxisols in 1960 because they had oxic horizons, but did not qualify for Oxisols in 1975 because they had an argillic horizon overlying an oxic horizon are, at the least, the "central concept" of the LAC-Oxisol interface.

Where are the LAC-Oxisol Interface Soils?

Unfortunately, there is no simple answer to this question. Examples have been reported from every soil moisture regime except the frigid and isofrigid soil temperature regimes. Many, and perhaps most, are in the intertropical zone with udic and ustic soil moisture regimes. They frequently are in topographic association with Oxisols (Moniz and Buol 1982; Moniz 1982; Lepsch and Buol 1974; Lepsch, Buol, and Daniels 1977<u>a</u>,<u>b</u>).

The LAC soils are not limited to acid conditions and commonly involve Alfisols, found most extensively in Western and Central Africa (Moormann, Lol, and Juo 1975; Moormann and Kang 1978; Sys 1972; Smith, Sys, and Van Wambeke 1975; Odell <u>et al</u>. 1974). Australia and South Asia also have extensive areas

of LAC-Oxisol interface soils (Coventry 1978, Isbell and Smith 1976, Isbell et al. 1977), including many in aridic soil moisture regimes of Australia. They are not, however, confined to tropical areas, and extensive areas are present in the southeastern United States and southeastern China. (Organizing Committee 1983, Buol 1979).

At this time, about the only regions where they have not been reported are in those parts of the world that were extensively affected by pleistocene glaciation. This includes those areas directly covered by ice, as well as those receiving melt water and associated loess well beyond the edge of the ice, as in the Mississippi river system of the United States.

Pedology of LAC-Oxisol Interface Soils

The oxic horizon is intended to characterize mineral subsurface horizons in an advanced stage of weathering as inferred by their mineralogy. The argillic horizon is an illuvial horizon formed by the accumulation of illuviated layer lattice silicate clays (Soil Survey Staff 1975). The concepts are not mutually exclusive. In soil formation, numerous events may take place simultaneously or in sequence to mutually reinforce or contradict each other (Simonson 1959). Therefore, there is nothing in genetic scenarios intended to characterize oxic and argillic horizons that render them mutually exclusive. It is imperative, therefore, that definitions in Soil Taxonomy create mutually exclusive classes. As with the other categories, however, modal concepts, type location, and typifying pedon methods of operation prevailed into the era of class-limit defined categories (i.e., Soil Taxonomy). With the "modal" Oxisols geographically removed, at least as far as Puerto Rico and Hawaii, it was difficult to test the interface soils from "modal" Ultisols in southeastern United States.

There is no reason to confine the pedogenic processes involved to only lessivage and weathering. Many other processes and sequences of processes can act to form soil profile morphologies and compositions commonly attributed to weathering and lessivage. The following are some pedogenic scenarios that may substitute for the classic concepts of weathering and lessivage.

Parent material composition consisting of quartz, kaolinite, and sesquioxides may have predetermined that one renders an interpretation of "highly weathered" to any soil forming thereupon. The observation may not correspond to any pedogenic process related to the present soil profile. The common, and probably extensive, occurrence of Oxisols on fluvial sediments

complete with stone lines and other sedimentary features strongly supports this mode of formation. Likewise, the presence of Oxisols in all soil moisture regimes, including the aridic, argues for weathering unrelated to present landscape surfaces.

Alteration of weatherable feldspar minerals to kaolinite under conditions of effective leaching (Marshall 1977; Calvert, Buol, and Weed 1980a,b) means that the clay mineral suites in soil and even saprolite from granite rocks can have the low CEC properties required for the oxic horizon. Kaolinite formation from 2:1 layer precursors is not as rapid.

There also are several scenarios that can produce the pedon morphology most frequently associated with lessivage and the argillic horizon. In a profile, clay content increase with depth is the most quantifiable criterion of the argillic horizon. But, how did that clay depth distribution form? Fluvial sediments commonly have a fining upward sequence, but an increase in energy may result in coarser fluvial deposits over finer textured sediments. Eolian activity can also create similar features. In material of similar composition (i.e., oxic properties with essentially no clear index mineral suites), there is no way to be sure if the surface horizon is a separate deposit or a modified part of the underlying sediment. The lack of any quantified definition of lithologic discontinuity points to the uncertainty with which investigators view its identification, especially in sediments that could be considered old and highly weathered.

The winnowing of fines from surface horizons may be responsible for many sandy textured surface horizons. By preferentially removing finer particles, erosion under natural vegetation, or perhaps acting in conjunction with small fields and thousands of years of shifting cultivation as practiced in ustic and udic soil moisture regimes of intertropical regions, may also cause the surface horizon to be more sandy than subsurface horizons. The author knows of no proof of this process, but notes it is frequently raised as a possibility.

Perhaps the greatest limitation to identifying the genetic nature of the truly illuviated argillic horizon has been the search for clay skins. In the 7th Approximation (Soil Survey Staff 1960), "something like" 10 percent oriented clays were specified in the cross section of thin sections of argillic horizons. As evidence became available that this volume was much too high for even the modal argillic horizons of Udalfs in Wisconsin-age loess (Buol and Hole 1961), the search for a new limit was undertaken. The lack of any clay skins in some Argid profiles (Buol and Yesilsoy 1964) and further work in

aridic and xeric soil moisture regimes (Nettleton, Flach, and Brasher 1969) led to removing any clay skin requirement in horizons where there was appreciable content of 2:1 expanding clays. About the same time, it was found that the Paleudults on the level surfaces on the Atlantic coastal plain had few if any clay skins in their typically massive or perhaps weak blocky structural "argillic" horizon (Cady and Daniels 1968; Gamble, Daniels, and Nettleton 1970). These papers, and numerous other observations, support the following description of Paleudults in Soil Taxonomy.

> Clay skins normally are not present in the upper part of the argillic horizon and are best preserved below a depth of 2 m, where biologic activity is low. The upper boundary of the argillic horizon is commonly abrupt and irregular. ...Weatherable minerals are virtually absent. Activity of the clay tends to be low and many are within the range of Oxisols. (Soil Survey Staff 1975)

In less deeply developed Udults, clay skins tend to be present throughout the argillic horizon but have greater longevity in the lower parts (Khalifa and Buol 1968). Only where argillans are coating nearly all blocky ped surfaces have they been found to retard nutrient uptake (Khalifa and Buol 1969). It is doubtful they have the same effect where less extensive.

Observing less clay skins in Paleudults than in Hapludults, one may conclude that with time argillic horizons evolve into oxic horizons. However, in thick mantles of material of oxic horizon composition, argillic horizons form on side slope positions (Moniz et al. 1982). Additions of silica, via lateral subsurface flow, also contribute to the formation of 2:1 silicate clays and higher CEC values in such positions, add support to the reversible nature of clay diagenesis, and reject the concept of a one-directional pathway of weathering in the soil system. The formation of blocky structure from massive or fine granular structure in oxic materials is explained by compression upon dessication following the complete relaxation of capillary tension during saturation. Blocky structure similar to that reported in Oxisols (Moniz and Buol 1982) has been observed in Paleudults of the Atlantic coastal plain (Southard 1983).

From these many observations of soils that neither conform to the modal or classical argillic horizon morphology, nor the modal or classical oxic horizon morphology, several genetic scenarios appear possible. Most likely, none of the scenarios operate independently, but rather in concert or sequentially to form the LAC-Oxisol interface soils. Some of the scenarios are as follows.

1. Lack of weatherable minerals can result from weathering *in situ* or deposition of preweathered material at the present site. Weathering during transport may play a role in certain sites.
2. Low activity clay in the profiles can result from the direct formation of kaolinite from feldspar *in situ* in a leaching environment or be inherited in the parent material via weathering at a remote site or in transport.
3. Lack of clay skins can be attributed to several factors.
   a. Absence of clay and weatherable minerals capable of weathering to layer silicate clays in the upper horizons, a condition likely in Arenic and sandy surface textured Typic Paleudults and Paleudalfs.
   b. Inability of percolating water to suspend silicate clay particles as in the fine granular structure and iron-rich surface horizons. As long as the environment from which clay could be mobilized remains oxidized, as in isotemperature regimes where no anaerobic horizons seasonally cover the soil, there is little possibility of suspending clay in the percolating water from iron granulate peds. This appears most probable in Oxisols in preweathered oxidized sediments as in the Brazilian shield area.
   c. Destruction of clay skins by pedoturbation processes is probable. Argilli-pedoturbation is not as likely because of the presence of low activity clays, but swelling from hydration as well as faunal and floral activity may be sufficient in an environment of very slow clay eluviation as suggested above. If clay skins are present in Paleudults or Oxisols, they are usually deep in the profile or more often in the rigid saprolite material below the solum.
   d. Dissolution and complete leaching of silicate clays is possible. Most of the LAC-Oxisol interface soils are in rather warm climates where desilication reactions are kinetically active. Illuviated clay on walls of large channels would appear to be particularly vulnerable during seasons of leaching.
   e. Even if silicate clays are illuviated to a subsoil horizon, they have to deposit on a rather stable surface of a channel or ped face to be observed as a clay skin. In the strong granular

structures characteristic of oxic horizons, illuviated clay may detected. The concentric banding pattern of the S-matrix in granular peds from oxic horizons hints of this fate of illuviated clay (Buol and Eswaran 1978). The lack of blocky structure, often described as massive, in Typic Paleudults would have a similar lack of stable ped surfaces for clay skin formation. Aquic Paleudults and Aquults usually have stronger grades of blocky structure in the horizon where low chroma mottles are first observed and clay skins or clay skin-like structures are probable (Southard 1983).

Selecting Criteria for Differences

Faced with these many reasons to mistrust evidence of clay skins as definitive of a pedogenic pathway and the extensive hectareage of argillic-oxic interface soils, attempts to clarify the definitions were inevitable. Before discussing proposed definitions, a brief review of desirable features of differentia is appropriate (Soil Survey Staff 1975).

1. We should classify a polypedon by its own properties.
2. The (soil-forming) processes themselves are not now suitable for use as differentia.
3. If the clay distribution is due solely to stratification of parent materials, few other statements can be made about the soil.
4. If genesis is ignored, the system will have reduced value. Genesis itself is unsuitable for direct use in soil classification. "Because the genesis of a soil cannot be observed or measured, pedologists may have widely differing opinions about it and the classification of a given polypedon would be affected by the background of the pedologist."
5. "The definitions of the taxa must be as explicit as possible to permit uniform application by many pedologists working independently."
6. Finally, "The definitions as now written will require changes as we gain experience by using the taxonomy....Probably no one person will approve of all the details of this system; few will be able to agree on all the desired changes."

Mineral Criteria for the Oxisols

The oxic horizon has been defined as: (1) having a fine earth fraction with "few or no primary minerals that weather to release bases, iron, or aluminum" (Soil Survey Staff 1975); (2) not having "more than traces of primary aluminosilicates such as feldspars, micas, glass, and ferromagnesian minerals" (Soil Survey Staff 1975); and (3) with "weatherable minerals (as defined later) that should constitute <3 percent (except 6 percent in dark red and dusky soils) of the fraction between 20-200 x 10^{-6} m, but mica (muscovite) may constitute as much as 6 percent of this fraction" (Soil Survey Staff 1975). In addition to the obvious confusion, these criteria do not mutually interface with either siliceous family criteria, that is, <10 percent weatherable minerals in the 20-200 x 10^{-6} m fraction or "Quartzi" criteria of <5 percent weatherable minerals in the sand fraction.

A definition of <10 percent weatherable minerals in the 50-200 x 10^{-6} m fraction, the 50 x 10^{-6} m lower limit inserted to facilitate grain counting, and the usual low content of silt in such soils is presently proposed in the working papers of the International Committee for Classification of Oxisols (ICOMOX) and used in this discussion. Also, in view of the very small amount of of sand in some very clayey Oxisols, it has been proposed that a total elemental limit of <40 cmol(p+)kg^{-1} of Mg^{+2}, Ca^{+2}, K^{+}, and Na^{+} be present in the soil, after coated gravel removal. The compatibility of the two criteria is being tested, and the total elemental criteria is strongly favored by many pedologists where such analyses are more readily available than grain counting.

Textural Criteria for the Oxisols

Currently, the oxic horizon and, thus, the Oxisol order are limited to clay contents greater than 15 percent. This not only limits the use of coarse-loamy families to a 3 percent range (15-18 percent clay) of clay but provides questionable associations of higher categories on the landscape. Coarse-textured Oxisols frequently mingle with Quartzipsamments. The Psamment being limited to loamy fine sand or coarser textures excludes many sandy loam s texture with less than 15 percent clay. Thus, there is a narrow range of Orthents, coarse-loamy since silt contents are usually very low, but less than 15 percent clay; they probably should be identified as Orthoxic, Ustoxic, and so on, if such subgroups were to be established. By lowering the Oxisol control section clay content requirement to 8 percent, the midpoint of the

sandy family line, and requiring a silt/clay ratio of <1, the taxonomic criteria allow the Oxisols to abut the Quartzipsamments. The silt/clay ratio is considered necessary to assure that loamy sand textured soils, not considered highly weathered as indicated by high silt contents, not classify as Oxisols (Van Wambeke 1962).

Argillic-Kandic-Oxic Interface

Perhaps the single most perplexing problem in the LAC-Oxisol interface is the inability to define, in explicit morphological terms, the difference between stratification and eluviation-illuviation. This is especially true where there is essentially little or no difference in mineralogical composition of two or more proposed strata and the present environment, or perceived paleoenvironments are intense or of long duration. At present there appear to be no technologies available to do this. Thus, we can advance the argument that stratigraphic deposition and eluvial-illuvial scenarios of producing a finer textured subsoil are equal for purposes of classification and in themselves not suitable for differentia. But the irregular distribution of organic carbon with depth can be taken as sufficient evidence of stratification to remove polypedons from consideration in the LAC-Oxisol interface taxa when this condition extends to a depth considered as taxonomically diagnostic (i.e., usually below 50 cm).

Structure of the subsurface horizon clearly is a morphological characteristic for consideration as a criterion. Oxisols classically have fine to very fine granular structure, and argillic horizons classically have angular or subangular blocky structure. However, when we have "weak, fine to medium subangular blocky structure breaking to fine granular or massive structure," a phrase commonly used in describing LAC-Oxisol interface soils, it is doubtful that we can view structural criteria as "permitting application by many pedologists working independently." In similar fashion, for the many reasons previously discussed, micromorphology becomes equally unsatisfactory within the LAC-Oxisol interface group of soils.

For these reasons, and with a strong impetus to provide as explicit a definition as possible, the search for criteria has gravitated to the rate of clay content change with depth. It is not without due consideration to the possibility that contrasting genesis may produce comparable morphologies but rather "because we want to be able to make the most important statements about taxa, [that] those properties that are important to plant growth and that

result from or influence soil genesis should be considered in the higher categories" (Soil Survey Staff 1975).

Figures 1a,b diagram the categories in the LAC-Oxisol interface that can currently be defined by various proposals.

1. Any pedon that meets the mineralogical and CEC requirements of an oxic horizon within 1 m of the surface becomes an Oxisol if the surface 18 cm, after mixing, contains more than 40 percent clay.
2. Oxisols with more than 40 percent clay in the surface 18 cm, after mixing, that have a rate of clay content increase greater than 8 percent absolute within a 15 cm thickness above a depth of 1.5 m are identified as "Kur" Great Groups of "Kuric" Subgroups of Oxisols (Figure 1a).
3. Of the soils that have less than 40 percent clay in the surface 18 cm, after mixing, those with Kandic horizons (i.e., 1.2 x clay content increase in a 15 cm thickness above 2 m), become Kandi or Kandhaplu Great Groups of Ultisols and Alfisols (Figure 1b).
4. There remain those soils with less than 40 percent clay in the surface 18 cm, after mixing, that have rates of clay content increase within a 2 m depth which are not rapid enough to qualify for kandic horizons but are rapid enough to qualify as argillic. No consensus is evident on where to classify such soils. They could be considered as oxic subgroups of Alfisols or Ultisols. This requires waiving the requirement of clay skins in argillic horizons with oxic horizon mineralogy and charge characteristics. They could be considered as argic subgroups of Oxisols. This alternative requires that the Oxisols Order definition include certain kinds of argillic horizons[2] (Figure 1b).

Rationale

The late Dr. Guy Smith strongly declined to discuss rationale for much Soil Taxonomy until after it was published. He believed that soil scientists would become hopelessly mired in debates about rationale and not get on with the task of testing proposed groups (Smith 1980). If soil scientists have learned from his activities, perhaps we can examine some of the rationale for

[2] The reader is cautioned that the above discussion and Figures 1a,b represent an unfinished stage in the ICOMOX committee work, and taxa suggested may never become part of Soil Taxonomy.

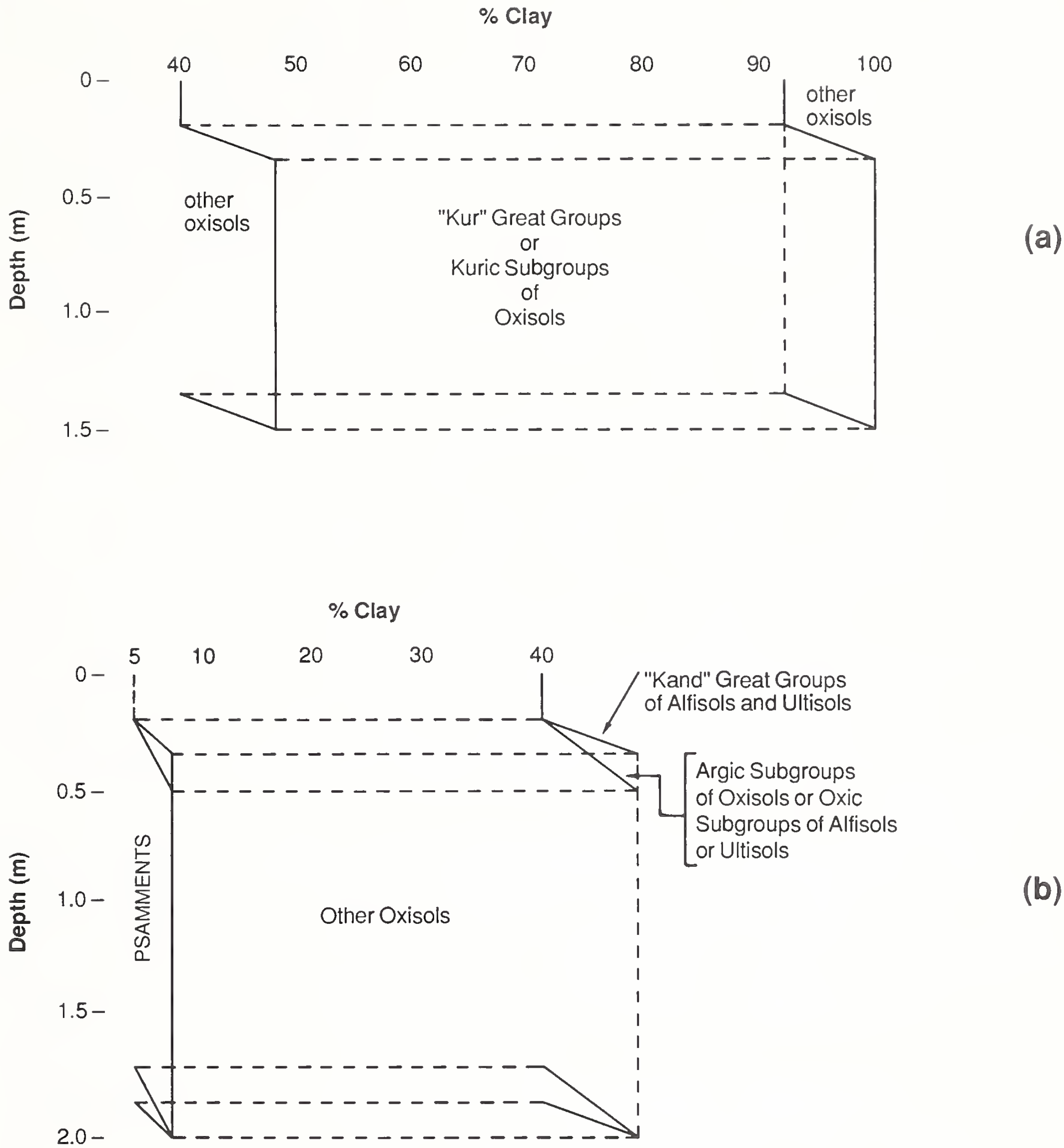

Figure 1. Schematic of LAC-Oxisols interface soils. All soils containing less than 10 percent weatherable minerals, apparent CEC <16 cmol(p+)kg^{-1} clay, and so on, as defined by the oxic horizon within 1 m of the surface are divided as having more than, or less than, 40 percent clay in the surface 18 cm after mixing. (a) Soils with more than 40 percent clay in the surface 18 cm and with a rate of clay content increase greater than 8 percent absolute within 15 cm thickness above 1.5 m are identified as Kur Great Groups or Kuric Subgroups of Oxisols. (b) Soils with less than 40 percent clay in the surface 18 cm and with kandic horizons become Kandi or Kandhaplu Great groups of Ultisols and Alfisols; those with clay content increases defined as argillic, but not kandic become either oxic subgroups of Ultisols and Alfisols or Argic Subgroups of Oxisols (requires Oxisols to accept some argillic horizons).

the LAC-Oxisol proposals without losing sight of the fact that we first need to examine the results of the proposed grouping. We should all feel free to debate the rationale only in the light of factual comparisons of groups.

Few people disagree with the recognition of mineral inertness defined by lack of weatherable minerals in the coarser fractions and low CEC values of the clay as criteria at a high level. Thus, the criteria that differentiate polypedons on the basis of increases in clay content with depth and increasing grade of blocky structure in the subsoil (these properties being frequently correlated) become the criteria available. The present proposals favor the clay content increase with depth criterion because it can be observed in the field and quantitatively evaluated in the laboratory. Mixing the top 18 cm is an attempt to keep cultivated and uncultivated soils in the same groups. The precedent for this has been set in several other categories. A diffuse horizon boundary, (i.e., thicker than 15 cm) was selected as the limit because of the correspondence to field manuals for describing soil (Soil Survey Staff 1981). Actually, the workshops had selected 12 cm as a compromise, and perhaps the value should be debated, but the convenience in being able to use a defined limit with established profile description vocabulary seems to outweigh the 3 cm difference.

In soils of oxic composition, the rate of clay content increase with depth seems to be less significant when the surface texture is fine. Forty percent was suggested as a class limit because it conforms to the lower limit of clay in the textural triangle. On the other end of the LAC-Oxisol interface, the proposal to lower the clay content to 8 percent clay but not sandy or loamy soil attempts to avoid a narrow gap between Psamments and Oxisols. It also enlarges the coarse-loamy family which presently in Oxisols is limited to clay contents of the control section between 15 and 18 percent.

Greatest disagreement on criteria is centered on soils of intermediate surface texture. At the core of the debate is our inability to consistently recognize argillic horizons--as defined by Soil Taxonomy--in LAC-oxic material. The agreement to eliminate any requirement of clay skins in kandic horizons recognize our technical limitations as well as the multiple hypotheses of soil genesis concerning clay content increases with depth in the soil. The proposal to recognize that kandic horizon as diagnostic, and utilize it to define LAC Great Groups, clarifies many previously insoluble debates about the presence of an argillic horizon. However, there remains a small taxonomic volume of LAC soils that do not have rapid enough clay content increase with depth (1.2 x

clay/15 cm) to qualify as kandic but do have rapid enough content increases with depth (1.2 x clay/30 cm) to qualify as argillic. Our inability to consistently identify the illuvial origin of the argillic horizon in many pedons in this group of soils poses a problem not yet fully addressed. In Figure 1b, the author suggests that they can either be "Argic" subgroups of Oxisols (this placement requires that exclusion of argillic horizons in the Order definition be removed), or as oxic Alfisols or Ultisols (in which case the requirement to demonstrate the illuvial genesis, (i.e. clay skins, of the argillic horizons with oxic mineralogical and charge characteristics should be waived).

As the author attempts to rationalize the proposals that have been made with respect to LAC-Oxisol interface, the following statements come forward. "Our goal has been a blending of many views to arrive at an approximation of a classification that seems as reasonable as we can hope to reach with our present knowledge. ...it has also given us faith in the value of improvement when we realize the utility of the old classifications (now including Soil Taxonomy) with all their imperfections" (Soil Survey Staff 1975).

One of the guidelines to the international committees is that proposed changes do minimum violence to the existing system. Within the continental United States that would argue for not enlarging the scope of Oxisols to include those pedons with clay content increases intermediate between argillic and kandic. However, in many other areas of the world, where correlation has proceeded more on the basis that lack of weatherable minerals and low apparent CEC values defined such soils, often after fruitless searches for clay skins, such soils have been included in Oxisols.

At this point the author would like to propose a rationale of practicality. Classificationists have more than exceeded the patience of their fellow soil scientists and administrators in the quest of the elusive clay skin in order to sort the LAC-Oxisol interface soil at the Order level. New criteria must be adopted that make it possible to "permit more uniform application by pedologists working independently" (Soil Survey Staff 1975).

Summary

The abrupt change in the definition of Oxisols between the 7th Approximation in 1960 and Soil Taxonomy in 1975, first including and then excluding the argillic horizons, created uncertainty regarding the Oxisol definition. Field identification difficulties and ultimately the technological

limitations to clay skin quantification in LAC soils have rendered consistent argillic horizon identification by competent soil scientists impossible. The desirability of identifying clay content increases with depth in a soil as either illuvial in process or the result of other processes is sharply questioned by many.

As a result of several years of study and debate by representatives of many countries, criteria have been proposed that would classify any soil with mineralogical properties of oxic composition as an Oxisol if the surface 18 cm, after mixing, contained 40 percent or more clay. Clay content increases of sufficient magnitude with depth would be recognized at lower categories of Oxisols.

Soils of oxic horizon mineralogical composition with less that 40 percent clay in the surface 18 cm but more than 8 percent clay in the control section would be recognized as Kandic Great Groups of appropriate Ultisols and Alfisols, if they had a rate of increase of clay content exceeding a 1.2 x clay content increase within a thickness of 15 cm. Failing to have this rate of clay content increase, they would be Oxisols.

A few LAC-Oxisol interface soils that have clay contents less than 40 percent in the surface 18 cm but with rates of clay content increase with depth intermediate between kandic and argillic horizons have not been specifically classified by present proposals. It is suggested that they become Oxisols by permitting the argillic horizons also conforming to oxic criteria, but not kandic horizons criteria, into Oxisols and that the presence of clay skins be totally waived in such soils.

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LOW ACTIVITY CLAY SOILS OF THE UNITED STATES

J.D. Nichols[1], D.E. Pettry[2], and L.P. Wilding[3]

Introduction

The preceding papers in this symposium have presented the proposed classification amendment to Soil Taxonomy (Soil Survey Staff 1975) and the requirements for placement in Kandic great groups. This paper describes, by major land resource areas, the extent of the soils that meet these requirements and examines the soil-forming factors for low activity clay soils in the continental United States.

Methods

To determine the extent of low activity clay soils, the data base was searched for soils meeting the Kandic requirements. The computerized data base includes the National Soil Survey Laboratory data from 1978 to the present, the Riverside Laboratory data, and data from Soil Survey Investigation Reports (SSIRs). In addition, the soils data used were not in the centralized computer banks from state laboratories, and data from federal laboratories were not included in the SSIRs. The initial computer search identified 163 soil series in the Alfisol and Ultisol Orders, where at least one pedon met the Kandic criteria. The data base was then searched using soil series names which had at least one pedon that met the LAC criteria in order to see how many pedons have those series names but do not meet the criteria. The list was reduced to 103 series upon closer examination of the data base and the evaluation of noncomputerized data.

An estimation of the percentage of low activity clay soils by major land resource areas (MLRAs) were made (USDA 1981). Several countries were selected frm each MLRA. The acreages of soil series which met the criteria were summed by counties, and the county figures were averaged to estimate the approximate extent for the MLRA. This procedure seemed adequate for this estimate, although it was realized that many series are not totally convertible to the proposed classification. Additionally, this procedure results in a

[1] Head, Soils Staff, USDA SCS, South National Technical Center, P.O. Box 6567, Fort Worth, TX 76115.

[2] Department of Agronomy, Mississippi State University, P.O. Box 5238, Starkville, MS 39762.

[3] Department of Soil and Crop Science, Texas A & M University, College Station, TX 77843.

conservative estimate. This procedure seemed adequate based upon the variation within the MLRAs. The part of MLRA 133A in eastern Mississippi is an exception where the percentage of LAC soils is lower than in the remainder of the MLRA. The data base was not adequate to determine the extent of low activity clay soils at the county level.

Extent of LAC Soils

The extent of LAC Ultisols and Alfisols in the U.S. is about 25 million ha. The percentages by MLRA of soils meeting the requirements for Kandic great groups of Ultisols and Alfisols are shown in Figure 1. Most of the Ultisols and Alfisols in the U.S. which met the Kandic requirement are located in the Southern Coastal Plain (133A), Southern Piedmont (136), and Carolina and Georgia Sand Hills (137). Kandic soils make up as much as 65 percent of these MLRAs. The Southern Appalachian Ridges and Valleys (128), Sand Mountain (129), Blue Ridge (130), North Central Florida Ridge (138), Atlantic Coast Flatwoods (153A), and South-Central Florida Ridge (154) have as much as 15 percent of the area composed of soils meeting the requirement. MLRAs that contain from 0.1 to 1 percent Kandic soils include the Western Coastal Plain (133B), Western Gulf Coast Flatwoods (152B), and the Southern Florida Flatwoods (155).

Classification of LAC Soils

Most soils which meet the low activity clay requirements are Udults. A few Udalfs and very few Ustults meet the requirements. Soils from coastal plain sediments are mostly Paleudults in typic, plinthic, and rhodic subgroups and mostly in the fine loamy particle-size family. A few soils derived from these sediments are in coarse loamy or coarse particle-size families while others are in clayey families. The extent of soils in arenic or grossarenic subgroups, and soils in aquic great groups and subgroups is notably small.

The LAC soils in the Southern Piedmont MLRA (136) are mostly Hapludults with lesser amounts of Rhodudults. Most are in a clayey family.

The LAC soils in the Southern Appalachian Ridges and Valleys MLRA (128) are mainly Paleudults in typic and rhodic subgroups. Most are in a clayey textural family.

The LAC soils in the Sand Mountain MLRA (129) are Paleudults in typic and rhodic subgroups and Rhodudults. Most are in a clayey family.

The LAC soils in the Blue Ridge MLRA (130) are mainly Hapludults in fine loamy and clayey textural families.

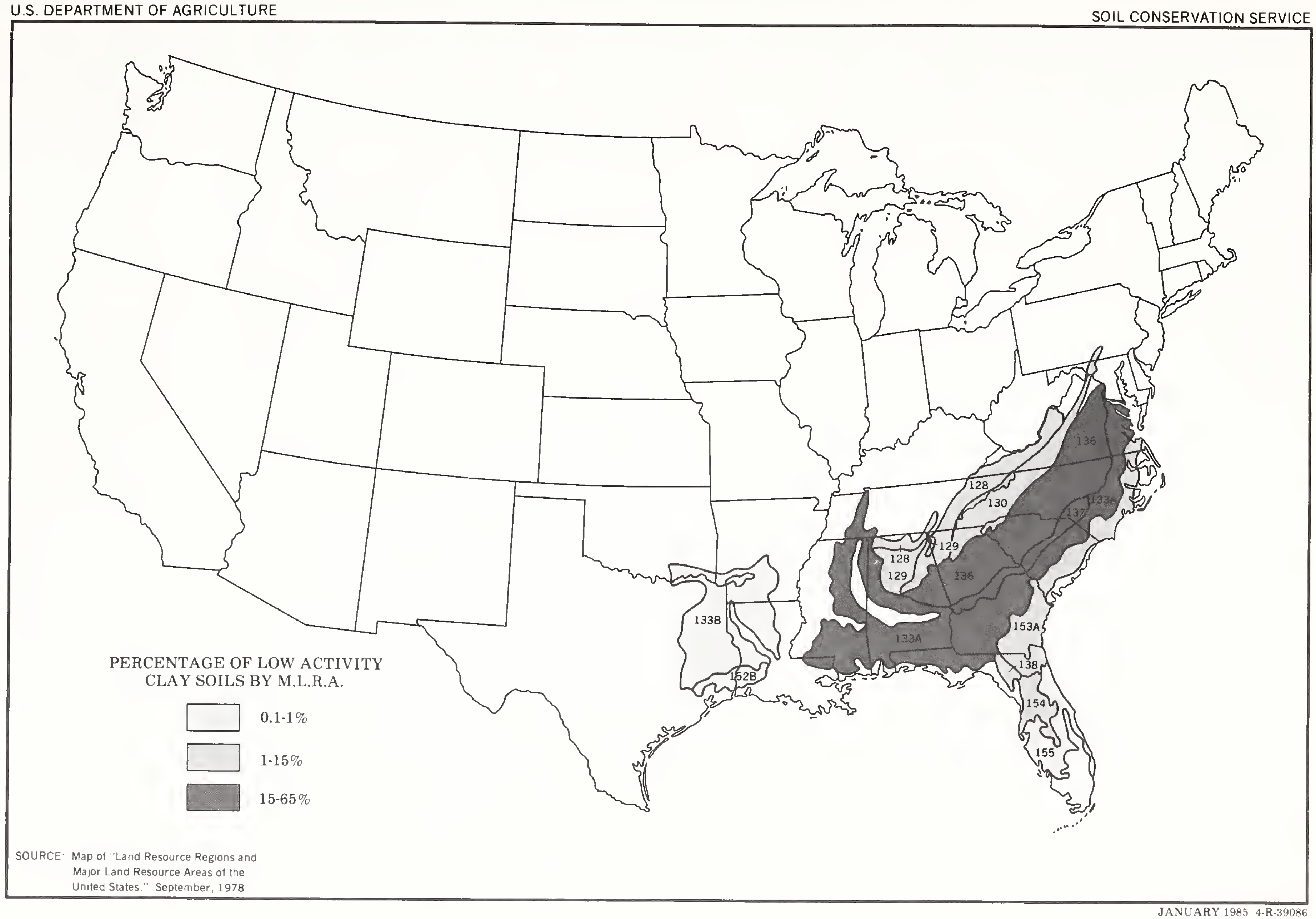

Figure 1. Low Activity clay soils of the United States by major land resource areas.

Factors in Soil Formation

Climate

The mean annual temperature ranges from 13° to 23°C. The highest concentration of soils with low activity clays occurs in areas that are near the average temperature for the range. The mean annual precipitation ranges from 1000 to 1600 mm. The highest concentration of low activity clays occurs in areas with about 1200 mm precipitation. Paleoclimatic periods may not have corresponded exactly with modern climatic conditions. The present temperature and precipitation may not represent long-term geological periods. However, the trend for increasing precipitation from west to east may have existed during geological periods even though the precise differentials may have changed over time. The lower precipitation toward the west is believed to be an important factor in the lower percentage of low activity clays in the Western Coastal Plain as compared to the Southern Coastal Plain because of expected lower leaching potentials and weathering rates.

Topography

The low activity clay soils occur above an elevation of about 7 m. The greatest concentration, however, occurs above 29 m. These soils occur mainly on nearly level to gently sloping upland interfluves on broad marine terraces and divides in the Coastal Plain, and on narrow divides and steep side slopes in the Piedmont Plateau. On the Southern Appalachian Ridges and Valleys, Sand Mountain, and Blue Ridge MLRAs, the LAC soils occur mainly on nearly level to gently sloping uplands and divides. Most of the soils are well drained, although some are moderately well drained and poorly drained. The internal drainage is considered adequate to move most bases to a considerable depth, in many cases below what has been considered as the solum. The soils do not occur on topographic positions that receive bases from higher elevations through percolating waters. Topography may also have had some effect on the lower marine terraces, where the overall generally smooth topography may have slowed the removal of bases from the system by deep percolation of water.

Biology

The low activity clay soils all had climax forest vegetation, primarily a mixture of pine and hardwoods, but this should be considered as reflecting current or recent conditions. No direct tie can be made between areas of low activity clay soils and biologic factors. One would expect, however, that

those areas subject to vegetation with low base cycling, such as pine trees, would also foster more acid weathering conditions and formation of low activity clays.

Time

These soils are on landscapes that are considered Pleistocene or older. They have been exposed to weathering for extended periods. Low activity clay soils make up a smaller percentage of the lower marine terraces than the higher ones and do not occur on the lowest terrace. This pattern of occurrence may reflect insufficient time for intense soil weathering. However, it is possible that lower terraces which have smaller areas of low activity clay soils had relatively high amounts of weatherable minerals and bases. This would add a parent material confounding bias to the time factor--a likely interaction found in most of the landscapes where low activity clay soils exist.

Parent Material

Marine sediments are the parent material of many low activity clay soils. The highest concentration of these soils is on the higher elevations of the Southern Coastal Plain. Areas on lower terraces have lower amounts of these soils, as does the Florida peninsula. The low activity clay soils that developed from marine sediments are soils with predominantly 18 to 35 percent clay in the particle-size control section, although coarser and finer textured soils are included. The Western Coastal Plain probably has a smaller percentage of low activity clay soils because the marine sediments had a higher content of bases and were subject to less intensive weathering. The additions of loess and pyroclastics are believed to have modified the marine sediments in this area. The marine terraces at lower elevation from Florida to Virginia may have had a greater content of bases and weatherable minerals than the higher terraces in this area, but it is likely that time is more important in their development.

The parent materials for low activity clay soils of Southern Piedmont and Blue Ridge are weathered from rocks that generally have been identified as granites, gneisses, and schists, although a number of other names have also been used. These acid rocks developed soils high in kaolinite and other low activity clays. The weathering has extended below the solum in many cases, and as much as several meters of saprolite occur between the soil and hard rock.

The parent materials for low activity clay soils in the Southern Appalachian Ridges and Valleys and the Sand Mountain MLRAs are weathered from limestone or sandstone and shales. Many of the sandstone and shale sediments were acid and kaolinite-rich upon deposition.

Summary

This study was made to determine the soils of continental United States that would be included in the proposed amendment to add low activity clay soils to Soil Taxonomy. A kandic horizon would be required in Alfisols and Ultisols at the great group level. The Southern Coastal Plain and the Southern Piedmont Major Land Resource Areas have the dominant acreage of low activity clay soils. Such soils make up as much as 65 percent of these areas. Minor acreages of these soils occur in other areas of the United States, mainly those adjoining the Southern Coastal Plain and Southern Piedmont areas. These soils are in the warmer, more humid parts of the United States on stable land surfaces, and have undergone intense weathering or were developed in preweathered sedimentary parent materials.

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CHEMISTRY OF LAC SOILS

A.S.R. Juo[1] and F. Adams[2]

Introduction

Soils with low activity clays (LAC) are widely occurring soils in the tropical and subtropical landscape. Among the common ones are the kaolinitic Alfisols in West Africa, the oxidic Oxisols in Cerrado Latin America, and the kaolinitic Ultisols in southern China and southeastern United States. The definition of LAC soils according to Soil Taxonomy (Soil Survey Staff 1975) is soils having effective CEC less than 16 meq/100 g of clay in the "control section" (i.e., B horizon). LAC soils normally contain predominantly kaolinite, Fe and Al oxides and hydrous oxides in the clay fraction. Thus, the chemical properties of such soils are characterized by low effective CEC and low ionic strength in the soil solution.

Research in soil chemistry in recent years has helped to dispel many earlier misconceptions. It has led to a better understanding of the properties and management of LAC soils. Chemical properties and surface charge characteristics of soil and minerals with variable charge have been reviewed by Gast (1977), Parfitt (1980), and Juo (1981). This paper attempts to cover a few selected topics on the chemistry of LAC soils that have practical application to soil fertility and soil management.

Charge Characteristics

A major feature of LAC soils is the dominance of variable charge colloids in the clay fraction (i.e., kaolinite, Fe, and Al oxides and hydrous oxides). The surface charge characteristics may be described by the following two types of electrical double layers on the basis of the mechanism by which free charges are distributed across a solid-solution interface:

A. a reversible double layer which exists on the surface bearing a constant potential or variable charge, and
B. a completely polarizable double layer which exists on the surface bearing a constant charge (Parks and de Bruyn 1962, Keng and Uehara 1974).

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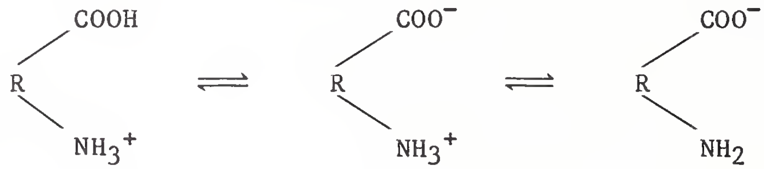
[1] Soil Scientist and Director, Farming Systems Program, IITA, Ibadan, Nigeria.
[2] Professor, Department of Crops and Soils, Auburn University, Alabama.

and hydrous oxides, kaolinite, and humified organic matter and microorganisms bear a variable or pH-dependent charge. Allophanes bear not only variable charge but also variable surfaces. The variable or pH-dependent charges on the surface of hydrous oxides of Al, Fe, and Si are originated by proton transfers at the amphoteric surface of these oxides.

$$\equiv MeOH_2^+ \rightleftharpoons \equiv MeOH + H^+$$
$$\equiv MeOH \rightleftharpoons \equiv MeO^- + H^+$$

Whereas the pH-dependent charges of soil organic matter are due to protolysis of functional amino and carboxyl groups on an organic surface:



The fundamental relationships among surface charge, electrical potential, and electrolyte concentration begin with the well-known Gouy-Chapman equation of electrical double layer which was developed primarily to deal with constant charge colloids (i.e., 2:1 clay minerals). In systems containing variable charge colloids, any changes in electrolyte concentration and pH of the system will result in changes of surface charge. Moreover, the Gouy-Chapman's diffuse double-layer theory has limited application due to the assumption that ions in solution behave as point charges and can approach the surface without limit (Gast 1977).

For variable charge colloids, such as Fe and Al hydrous oxides, the Gouy-Chapman equation applies at lower surface potentials (<25 mV), whereas the Stern modification of Gouy-Chapman's equation applies at higher potentials (Parks 1967).

In systems of variable charge colloids where H^+ and OH^- are potential determining ions, the surface potential is related to H^+ concentration by a Nernst-type equation:

$$\psi_o = \frac{KT}{e} \ln \frac{H^+}{H_o^+} \qquad (1)$$

Where ψ_o is the surface potential in statvolts; $\underline{e}$ is electron charge in electrostatic units (esu); and H_o^+ is the hydrogen ion activity when ψ_o is zero. Equation (1) shows that ψ_o is constant when pH is constant.

At low ψ_o (<25 mV) and in the absence of specific absorption, the Gouy-Chapman equation may be written as follows (Uehara and Gillman, 1980).

$$\delta_v = \left(\frac{2n\epsilon KT}{\pi}\right)^{1/2} \text{Sine } 1.15z\,(pH_o - pH) \qquad (2)$$

where,

δ_v = variable surface charge density (esu/cm^2)

n = electrolyte concentration (# $ions/cm^3$)

ϵ = dielectric constant of the solvent

K = Boltzmann constant (erg/ion °K)

T = absolute temperature (°K)

z = counter ion valence

pH_o = point of zero charge (PZC)

For 1:1 indifferent electrolyte, equation (2) becomes:

$$\delta_v = 1.67 \times 10^{-6}\, n^{1/2}\, (pH_o - pH) \qquad (3)$$

Here, the pH_o or point of zero charge (PZC) is the pH value of soil solution at which there is no net surface charge on the soil particles (Parks 1967).

The PZC and surface charge of soil and oxide systems can be determined by potentiometric titration as a function of pH and electrolyte concentration, or by measuring the counter-ion retention using an indifferent electrolyte such as NaCl and $NaNO_3$ (Schofield, 1949, Van Raij and Peech 1972, Breeuwsma and Lyklema 1973). Published data of pH-charge curves of soil and oxide systems reveal the following features as illustrated in Figure 1 (Van Raij and Peech 1972; Keng and Uehara 1974; Hingston, Posner, and Quirk 1972; Gallez, Juo, and Herbillon 1976; Gillman and Bell 1976; Laverdiere and Weaver 1977; Hendershot, and Lavkulich 1983).

1. In the absence of permanent negative and positive charges and in the absence of specifically adsorbed cations and anions, the intersection of pH-charge curves determined in 1:1 indifferent electrolyte occurs on the line of zero net surface charge ($\delta = 0$) as shown in Figure 1c.
2. In cases where the solid phase contains an appreciable amount of permanent positive or negative charge, or in the presence of specifically adsorbed ions such as Ca^{+2} and SO_4^{-2}, the intersection of the pH-charge curves may shift upward or downward with reference to the "zero charge line" (Figures 1a,b).

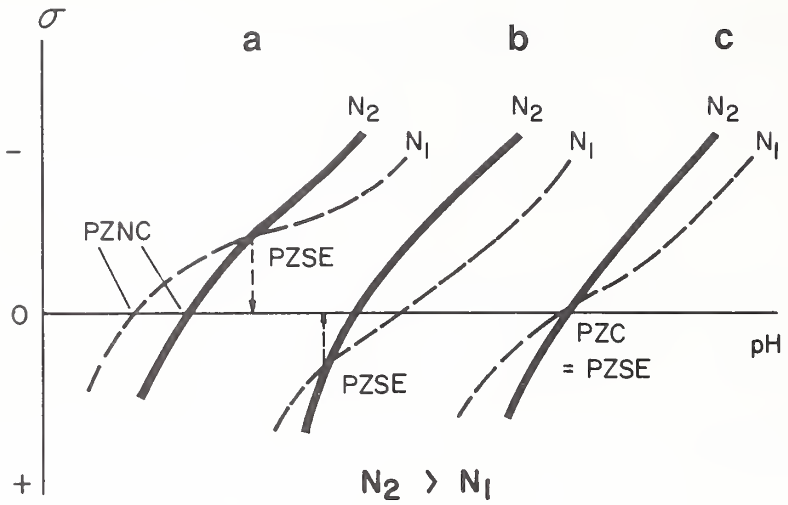


Figure 1. An illustrative plot showing various points of zero charge (PZC, PZSE, and PZNC) (Sposito 1981).

The presence of an appreciable amount of permanent charge (i.e., smectite) and soil organic matter (i.e., surface soil horizons) in a soil or oxide system causes the intersection of the pH-charge curves to shift to a lower pH value (Laverdiere and Weaver 1977, Van Raij and Peech 1972). Moreover, the presence of a specifically adsorbed cation or anion may also shift the point of intersection to lower or higher pH values relative to that determined in 1:1 indifferent electrolyte (Keng and Uehara 1974; Gallez, Juo, and Herbillon 1976).

The intersection of the pH-charge curves from the potentiometric titration is called "point of zero salt effect" (PZSE) as illustrated in Figure 1 (Parker et al. 1979). In Figure 1c, PZSE equals "the point of zero charge" (PZC). In Figures 1a and b, the PZSE shifts upward or downward relative to the "zero charge line." Such PZSE may be termed "apparent" PZC.

The point of zero charge (PZC) is the pH value of the solution at which there is no net charge on the solid particles (Parks 1967, Pyman et al. 1979). The point of zero salt effect (PZSE) is the pH value at which there is no change in density of the H^+ (δH) with a change in the ionic strength of the solution phase. Thus, the common points of intersection of the pH-charge curves of soil systems indicates PZSE or "apparent" PZC.

Another parameter illustrated in Figure 1 is the point of zero net charge (PZNC). The PZNC is defined as the pH value at which the cation-exchange

capacity (CEC) equals the anion-exchange capacity (AEC) of the soil (Uehara and Gillman 1980, Sposito 1981). Conventionally, PZNC is determined through measurement of surface cation and anion excesses in a soil after saturation of the soil with an index salt solution (Schofield 1949, Van Raij and Peech 1972, Parker et al. 1979).

A more precise theorectical relationship of the PZC of a soil to PZSE and PZNC (point of zero net charge) has been described by Sposito (1981). The balance of surface charge in a soil containing an aqueous solution phase is expressed directly in terms of the five surface charge densities:

$$\delta_O + \delta_H + \delta_{IS} + \delta_{OS} + \delta_D = 0, \qquad (4)$$

where, δ_O = surface density of permanent positive or negative charge;

δ_H = surface density of new proton charge;

δ_{IS} = inner-sphere complex charge which is equal to the net total surface charge of the ions other than H^+ and OH^- (e.g., sulfate, phosphate, and group II metal cations);

δ_{OS} = surface charge density of outer-sphere complex charge which is equal to the net total surface charge of the ions that have formed outer-sphere complexes with surface functional groups;

δ_D = surface charge density of dissociated charge which is equal to minus the net total interfacial charge neutralized by the ions in the soil solution that have not formed complexes with surface functional groups.

The sum of ($\delta_O + \delta_H$) is the surface charge density, δ, in the double-layer model. The sum ($\delta_{IS} + \delta_{OS}$) is equal to the surface charge density of the Stern layer. The equivalent surface charge density, δ_D, would be associated with the diffuse portion of the electrical double layer. The definitions of some points of zero charges and the isoelectric point in soils are given in Table 1.

The pH-charge curves (Na-saturated, 1:1 indifferent electrolyte) of an Fe oxide-rich Rhodustalf (derived from basalt) and a kaolinitic Haplorthox (derived from alluvium) are shown in Figures 2 and 3. The apparent PZC or PZSE of the Rhodustalf B_{22t} occurs below the "zero charge line" at pH 3.88, indicating the presence of appreciable permanent negative charge in the soil;

Table 1. Definitions of some points of zero charge in soils (Sposito 1981).

Symbol	Name	Condition
PZC	Point of zero charge	$\delta_D = 0$
PZSE	Point of zero salt effect	$(\Delta \delta_H / \Delta_I)_T = 0$*
PZNC	Point of zero net charge	$\delta_{OS} + \delta_D = 0$
PZNPC	Point of net proton charge	$\delta_H = 0$
IEP	Isoelectric point	$\delta_H = 0$
		$\delta_0 = \delta_{IS} = \delta_O = 0$

* I = ionic strength; T = absolute temperature.

whereas, the pH-charge curves of the Haplorthox B_{22} intersect at pH 3.66 where PZC = PZSE.

The pH-charge curves and the apparent PZC values are useful parameters for soil characterization. For example, the pH-charge curves of oxide-rich Rhodustalf B_{22t} (Figure 2) exhibit much larger change in surface charge due to change in pH and electrolyte concentration as compared with the kaolinite-rich Haplorthox B_{22} (Figure 3).

An inventory of published data of PZC indicates that most LAC soils (Alfisols, Ultisols, and Oxisols) occur between pH 4 and 6 (Van Raij and Peech 1972; Keng and Uehara 1974; Gallez Juo, and Herbillon 1976; Gillman and Bell 1976); whereas, the PZC values of Fe and Al oxides and hydrous oxides occur between pH 7 and 9 (Table 2). Thus, in soil systems, Fe and Al oxides would only contribute to anion absorption considering the pH values of most LAC soils (i.e., pH 4 to 6). Furthermore, the relatively low PZC values of LAC soils indicate that most of the LAC soils are still well supplied with silica. Tropical soil weathering is essentially a process of desilication (Herbillon 1981). Therefore, a soil with a high degree of desilication would give a relatively high PZC value.

Specific Surface Area, CEC, and AEC

Cation- and anion-exchange capacities of a soil are the product of the specific surface area, S, and the surface charge density.

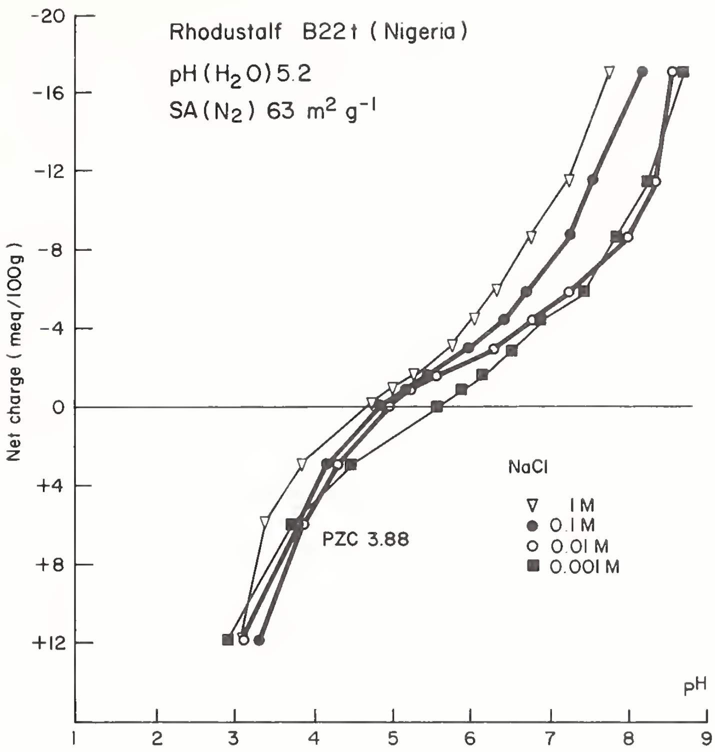


Figure 2. The pH-charge curves of B_{22} horizon of an oxidic Alfisol (Rhodustalf) derived from basalts in Nigeria (unpublished data, A.S.R. Juo).

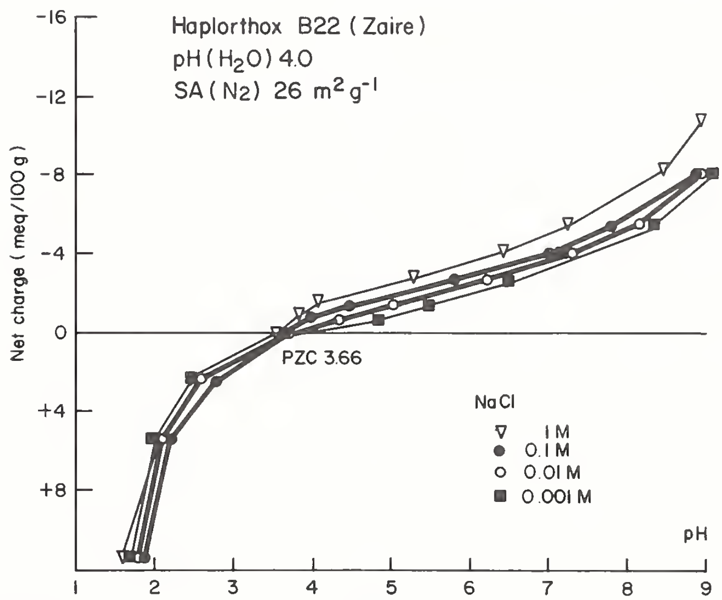


Figure 3. The pH-charge curves of B_{22} horizon of a kaolinitic Oxisol (Haplorthox) derived from sandy alluvium in Zaire (unpublished data, A.S.R. Juo).

$$CEC = S\delta_{-} \text{ (in meq/cm}^2\text{)}$$
$$AEC = S\delta_{+} \text{ (in meq/cm}^2\text{)}$$

In most LAC soils, the amounts of permanent negative and positive charge are often small, CEC and AEC mostly arise from pH-dependent charge on the surface of oxide minerals and organic matter. The magnitude of the CEC or AEC of a LAC soil, therefore, depends upon its natural soil pH relative to its PZC as well as the specific surface area of the soil colloids.

There are two major inorganic constituents, namely, kaolinite and Fe oxides, that contribute to the CEC and AEC of LAC soils. Kaolinite generally has a small specific surface area (15-30 m^2/g) and small, if not negligible, amounts of permanent charge. Its pH-charge curves show little change in negative or positive charge within the common range of soil pH (i.e., pH 4 to 6). The Fe oxides and hydrous oxides may occur in small particle sizes with relatively large specific surface areas (i.e., 150-300 m^2/g) in some LAC soils. However, in LAC soils, a significant portion of Fe hydrous oxides in

Table 2. Specific surface area (BET-N_2) and point of zero charge (PZC) of soil minerals. (Sources: Parfitt 1980, Stumm and Morgan 1981, and Breeuwsma and Lyklema 1973.

Minerals	SA-N_2 (m^2 g^{-1})	PZC (pH)
Gibbsite	45	9.5
Goethite	80	8.1
Hematite	150	7.5
Ferrihydrite	260	6.9
Hydrated SiO_2	3	2.0
Kaolinite	15	4.6
Smectite	700 (EG)†	2.5
Allophane	800 (EG)	6.5

† EG as determined by ethylene glycol retention.

the clay fraction may exist as surface coatings. Consequently, their specific surface area is greatly reduced (i.e., 50-100 m^2/g). Specific surface area of soil Fe oxides may be estimated by BET-N_2 adsorption by soil or clay samples before and after removal of free Fe_2O_3 with dithionite (Deshpande Greenland, and Quirk 1968; Gallez, Juo, and Herbillon 1976). The large surface area of the small Fe oxide particles in the clay fraction of many LAC soils derived from basalts and other ferromagnesian rocks may also be estimated from their electron micrographs (Greenland and Oades 1968).

The BET-N_2 specific surface area and the derived specific surface area of soil Fe_2O_3 calculated from samples before and after dithionite treatment for selected LAC soils are given in Table 3. As shown in this table, Fe oxides in the first six samples have much larger specific surface area than the remaining four soils. This seems to suggest that Fe oxides in the soils derived from basic parent rocks such as bbasalts, diabase, and limestones apparently exist as very small discrete particles; whereas an appreciable amount of Fe oxides in the soils derived from acidic parent rocks may occur as surface coatings on kaolinite and other layer silicate minerals in the clay fraction.

The effect of Al oxides on the CEC and AEC is less clear. Gibbsite is the only known Al oxide mineral found in soils. It occurs in some LAC Ultisols and Oxisols, but in relatively small amounts. Moreover, gibbsite tends to form relatively large particles with smaller specific surface area as compared with Fe oxides (Table 1).

Published data on specific surface area and PZC of LAC soils indicate that both parameters could be useful criteria for Soil Taxonomy, particularly for classifying "oxidic" soils from "non-oxidic" ones. The LAC soils may be regarded as mixed systems of quartz, kaolin, Fe and Al oxides, and hydrous oxides. Quartz and kaolinite have PZC values below pH 3.0, whereas pure Fe and Al oxides, and hydrous oxide minerals have PZC values above pH 7.0. Thus, the higher the degree of desilication of a soil, the higher the PZC value tends to be, or the more "oxidic" the soil becomes. Furthermore, Fe oxides in "oxidic" soils tend to exist in small discrete particle sizes with large specific surface areas (Gallez, Juo, and Herbillon 1976; Juo 1980). As also shown in Table 3, LAC soils with "high specific surface area" Fe oxides generally have low bulk density. Such soils tend to have more stable microaggregates and low water-dispersable clays particularly those when soil pH is very close to the PZC (Gillman and Bell 1976, Juo 1981).

Table 3. Specific surface area (BET-N_2) of soil and the derived specific surface area of Fe_2O_3 of selected LAC soils (A.S.R. Juo, unpublished data).

No.	Soils	Parent material	Clay %	Fe_2O_3 %	BET-N_2 Specific surface area m^2/g soil	Derived specific surface area m^2/g Fe_2O_3	Bulk density g/cm^3
1.	Plinthohumult B_2, New Zealand	Basalt	56	21.5	85	355	--
2.	Rhodustalf B_{22t}, Nigeria	Basalt	54	8.9	73	257	1.04
3.	Acrohumox B_2, N. Australia	Basalt	58	24.9	76	199	--
4.	Tropohumult B_{2t}, Hawaii	Basalt	--	21.2	70	320	0.98
5.	Paleudult B_{21t}, Brazil	Diabase	59	15.8	59	201	1.07
6.	Eutrorthox B_{22}, Puerto Rico	Limestone	87	16.6	55	186	--
7.	Paleustalf B_{2t}, Nigeria	Banded Gneiss	54	7.2	30	56	1.49
8.	Acrustox B_{21}, Brazil	Acidic Gneiss	55	13.1	30	66	--
9.	Paleustalf B_{23t}, N. Australia	Sandstone	38	5.4	31	84	--
10.	Paleustult B_{21t}, Nigeria	Sandstone	64	10.4	41	110	1.38

It is evident that the two major inorganic constituents, namely kaolinite and Fe oxides in LAC soils contribute little to the cation-exchange capacity. Kaolinite has little surface area and bears a relatively small surface charge. Iron oxides though have relatively large surface areas but bear little or no negative charge within the pH range commonly occurring in LAC soils (i.e., pH 4 to 6).

Soil organic matter thus contributes a major portion of the CEC in the surface horizons of LAC Alfisols and Oxisols with pH (H_2O) value greater than 5.0. Whereas in the more acidic LAC Ultisols and Oxisols with pH (H_2O) below 5.0 the effect of organic matter on CEC becomes less pronounced (Figure 4).

For soils containing predominantly variable charge colloids, conventional methods for measuring CEC at high electrolyte concentration and neutral pH become less meaningful. A more realistic method of CEC measurement would be to determine the net electrical charges of the soil in a dilute unbuffered

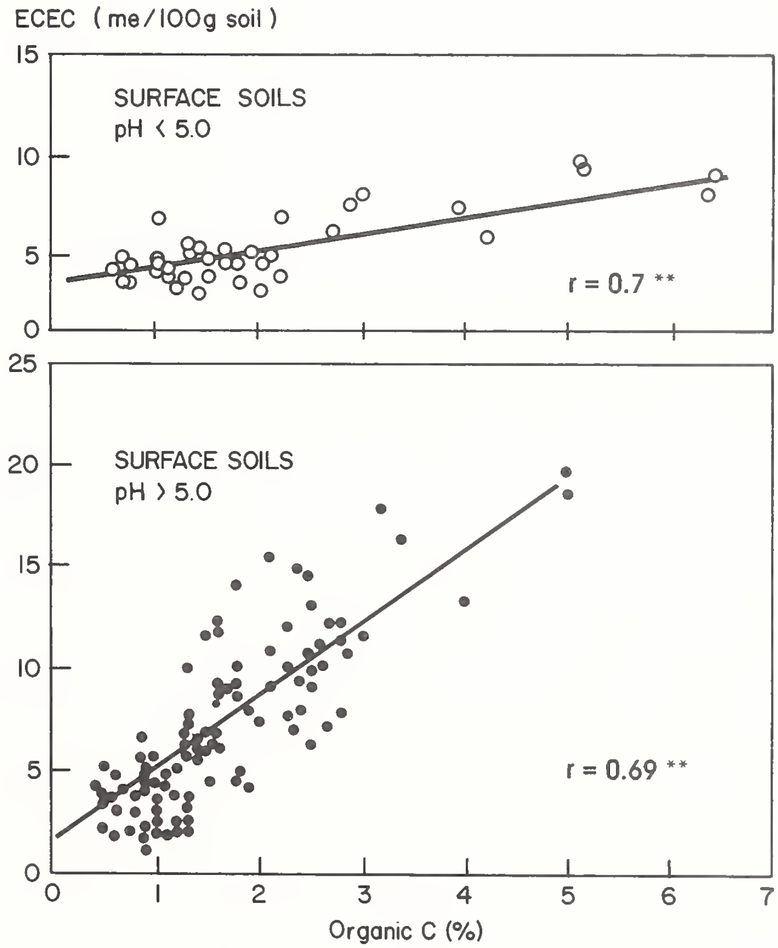


Figure 4. Effect of organic matter on effective CEC in LAC soils above and below pH 5.0.

electrolyte solution with a concentration similar to that encountered in the LAC soil solution. This would involve the determination of positive and negative charges using a procedure similar to that described by Schofield (1949). The values of negative and positive charges of the subsoil horizons of some LAC soils measured in 0.01M NaCl solution are given in Table 4 (Gallez, Juo, and Herbillon 1976). There was good agreement between the amount of negative charge and the effective CEC.

The Schofield method is, however, time-consuming and unsuitable for routine analyses which deals with large numbers of samples. Thus, the effective CEC (ECEC), which is the sum of M NH_4OAc extractable Ca, Mg, K, and Na plus unbuffered M KCl extractable Al and H, probably gives more realistic values closer to field conditions (Coleman and Thomas 1967, Kamprath 1970, Juo *et al*. 1975).

The CEC and base saturation are important criteria for soil classification. The use of the Mehlich's method (Black 1965) of sum of cations for LAC soils often gives unrealistically large CEC values resulting from the overestimation of exchange acidity by $BaCl_2$·TEA leaching at pH 8.2. The commonly used M NH_4OAc displacement method (Black 1965) would also give higher CEC values because of high electrolyte concentration and high pH condition. The effective CEC method has been adopted by the soils laboratories at the International Institute of Tropical Agriculture and many other soil

Table 4. Postive and negative charges determined by Cl^- and Na^+ adsorption at pH 3 in 0.01M NaCl and effective CEC determined by sum of M NH_4OAc extractable base and M KCl extractable acidity for three LAC soils from Nigeria (Gallez, Juo, and Herbillon 1976)

Soil	Electrical charge (meq/100)		Effective CEC meq/100g
	Positive	Negative†	
Paleustalf B_{2t}	0.6	4.1	4.7
Paleustult B_{21t}	0.4	1.3	1.8
Tropohumult B_{21t}	2.1	5.7	4.4

† With correction of adsorbed Al^{+3}.

laboratories in the tropics as a standard method for CEC determinations. A comparison of the CEC values of some LAC soils measured by the three conventional CEC methods are given in Table 5.

Anion Adsorption

LAC soils may retain appreciable amounts of anions such at nitrate as the positively charged sites on the Fe and Al oxide surfaces. Anion-exchange capacity (AEC), however, is a less useful parameter for soil characterization. This is because most anions are adsorbed by soils not only through the mechanism of simple ion exchange, but also through specific adsorption and ligand exchange as well. Anion adsorption by soils and soil materials have been reviewed by Parfitt (1978, 1980) and Bowden, Posner, and Quirk (1980). For oxide-rich LAC soils, the affinity of anions generally follows the order:

phosphate > assenate > selenite = molybdate =
fluoride > sulfate = silicate > chloride > nitrate.

For LAC soils, adsorption of phosphate and silicate deserves special attention. The former bears special importance to soil fertility management; whereas the latter provides useful information on degree of weathering and surface reactivity of Fe and Al oxides in soils (Gallez et al. 1977).

Table 5. Cation-exchange capacity of B-horizons of four LAC soils as determined by three conventional methods (Juo, Ayanlaja, and Ogumwale 1976).

Soil (B Horizon)	pH (H_2O)	Clay (%)	Cation-exchange capacity (meq/100g)		
			Effective CEC	NH_4OAc (pH 7)	$BaCl_2$-TEA (pH 8.2)
Alfisol, kaolinitic	6.0	54	5.3	7.3	14.5
Ultisol, kaolinitic	4.5	34	2.5	5.2	7.0
Alfisol, oxidic	5.8	68	8.9	9.6	26.2
Oxisol, oxidic	5.3	56	4.9	10.9	17.6

Phosphate Adsorption

Iron and aluminum oxide minerals with high specific surface area are primarily responsible for the adsorption of phosphate as well as other anions in many LAC soils (Gallez and Herbillon 1977, Juo and Fox 1977). Adsorption of phosphate on an oxide surface may involve both electrostatic interaction and chemical interaction (Parfitt, Russell, and Farmer 1978; Bowden, Posner, and Quirk 1980). In Fe and Al oxide systems, phosphate adsorption is affected by pH, and adsorption envelopes had a maximum near pH 4.0 in solutions containing low P concentrations (Hingston, Posner, and Quirk 1972; Chen, Butler, and Stumm 1973; Huang 1975; Parfitt _et al_. 1977). Phosphate adsorption on Fe and Al oxide surfaces was decreased with the presence of organic chelating ions (Chen, Butler, and Stumm 1973) and silicate ions (Hingston, Posner, and Quirk 1972). Interpretation of these data is difficult, since both the phosphate and Fe or Al hydrous oxides can accept or release proton. It was suggested that on Al hydrous oxide surfaces, at pH 4, $H_2PO_4^-$ was adsorbed initially on $AlOH_2^+$ sites; with increasing phosphate coverage, AlOH sites reacted to form monodentate complexes (Rajan and Watkinson 1976). In the case of Fe hydrous oxides such as geothite, infrared studies showed direct evidence for the formation of a binuclear bridging $Fe\text{-}OP(O)_2O\text{-}Fe$ surface complex over the whole range of surface coverage (Parfitt, Russell, and Farmer 1976).

Phosphate sorption capacity was found to correlate significantly with soil properties such as BET-N_2 specific surface area, exchangeable Al, and to a lesser extent, clay and extractable Al and Fe oxide contents (Syers _et al_. 1973, Udo and Uzu 1972, Juo and Fox 1977, LeMare 1981).

In high base status soils, organic matter can block sites on Fe and Al oxides and reduce phosphate adsorption (Hashimoto and Takayama 1971; Weir 1972; Moshi, Wild, and Greenland 1974). The influence of organic matter on phosphate adsorption by oxidic surfaces is more evident within the same soil profile as in the case of an Fe oxide-rich Alfisol (Rhodustalf) from southern Nigeria (Table 6).

On the other hand, soil organic constituents such as fulvic acid and humic acid may form complexes with Fe and Al ions (Schnitzer 1969). Thus, in strongly acidic LAC soils (i.e., most Ultisols and Oxisols in the high rainfall tropics), Fe and Al components on soil organic matter may also play an important role in the adsorption of phosphate (Parfitt 1978). Organoaluminum complexes in acid LAC soil may be estimated by extracting the soil with $CuCl_2$ (Juo and Kamprath 1979).

Table 6. Phosphate adsorption by an Alfisol (Rhodustalf) from Southern Nigeria as a function of depth and organic carbon content (unpublished data, A.S.R. Juo).

Horizon	pH (H_2O)	Organic C (%)	Clay (%)	Diothionite-Fe_2O_3 (%)	SPR† P ug/g soil	Calculated SPR P ug/g Fe_2O_3
A1	6.5	1.63	38	12.87	115	894
B1	6.4	1.17	50	13.37	160	1197
B_{2t}	5.8	0.27	57	13.08	390	2982
B_3	5.6	0.17	48	12.02	375	3120

† SPR = Standard P requirement, or P adsorbed by soil at 0.2 ppm P in equilibrium solution (Juo and Fox 1977).

Several workers demonstrated the significant increase in CEC due to phosphate adsorption in some oxide-rich LAC soils (Mekaru and Uehara 1972, Juo and Maduakor 1974, Wann and Uehara 1978). This may be explained by the mechanistic model of anion adsorption on goethite decreases as adsorption of phosphate proceeds. As a common soil pH value, for example pH 6, the net positive charge will decrease as phosphate is adsorbed. The net surface charge eventually becomes negative at high surface charge. This charge reversal accounts for the increase in CEC and the flocculation-dispersion properties of phosphate soils (Wann and Uehara 1978).

Oxisols and Ultisols with high "specific surface area oxides" are well-known for their good physical properties (such as low bulk density and high aggregate stability) and poor chemical properties (such as low effective CEC and high phosphate fixation). The coexistence of substantial positive and negative charges at field pH values gives rise to electrostatic bonding between soil constituents. This electrostatic contribution to aggregate stability is, however, pH-dependent (El-Swaify 1980, Tama and El-Swaify 1978). Therefore, the soil amendment effect of phosphate application and liming may require long-term field verification. Large dosages of phosphate or lime may increase the soil CEC substantially; on the other hand, it may change the soil physical properties of these oxidic soils from a favorable to an unfavorable condition in the long run.

Desilication Silica Adsorption

Desilication is among the important processes of tropical soil weathering. Thus, both the content of soluble silica in soil solution and the capacity of soils to adsorb added soluble silica may be useful criteria for soil characterization (D'Hoore and Coulter 1972; Gallez and Herbillon 1977; Herbillon, Gallez, and Juo 1977). This is because the oxidic surfaces of Al and Fe oxides are much more reactive to soluble silica than the silicated surface of clay minerals (Beckwith and Reeves 1963, McKeague and Cline 1963).

Silica occurs in soil solution as silicic acid $Si(OH)_4$. Adsorption generally increases with pH up to pH 9.0 which equals the pK_1 for silicic acid dissociation (Parfitt 1978).

$$Si(OH)_4 = H_3SiO_4^- + H^+$$

Adsorption maximum of monobasic silicate ion, $H_3SiO_4^-$, by soils and Fe and Al oxides--such as goethite, hematite, and, gibbsite--occurs near pH 9.2 (Hingston, Posner, and Quirk 1972; Beckwith and Reeves 1963; Obihara and Russell 1972). The silica adsorption capacity of minerals common in LAC soils follows the order gibbsite > goethite >> kaolinite, and soils generally show a similar trend in accordance with their mineralogical composition (Gallez and Herbillon 1977). Consequently, silica adsorption data determined at pH 9.2 should provide a good measure of the type of surface in soils as well as the degree of desilication of the soils. Thus, two easily measured parameters, namely, the index of silica reactivity (ISR) and the index of silica saturation (ISS) were proposed for the above purposes (Gallez and Herbillon 1977; Herbillon, Gallez, and Juo 1977). The ISR is defined as the percentage of soluble silica lost from a solution brought into contact with a soil sample. The ISS is defined as the ratio of the amount of soluble silica that a soil releases into the solution phase when equilibrated with a dilute, unbuffered salt solution, divided by the amount of silica adsorbed by the same soil at pH 9.2. The ISR values of soils were shown to be sensitive to both the nature and the magnitude of the oxidic surfaces present in soils; whereas, the ISS values can be used to describe the pedogenetic environments of weathering and soil formation.

Soil Solution in LAC Soils

The soil solution plays a vital role in soil-plant interrelations. It is the medium in which soil chemical reactions occur and from which roots draw the plant's supply of inorganic nutrients. The chemical constituents contained in

these solutions depend upon the mineral and organic solid-phase components of that soil and are supplemented by amendments of fertilizers and lime.

Since LAC soils are the near-end products of mineral weathering, they have been subjected to extensive leaching over time and their capacity to supply nutrient ions by dissolution of minerals has been almost exhausted. Consequently, the ionic strength of LAC soil solutions are very low in the absence of recent fertilizer additions. Gillman and Bell (1978) analyzed soil solutions from several highly weathered profiles in tropical Queensland, Australia, and found ionic strengths of surface soil solutions to range between 0.001 and 0.01. Numerous surface soil solutions of Ultisols in Alabama, United States, have consistently had ionic strengths near 0.005 when sampled in early spring prior to fertilizing and planting (unpublished data, F. Adams, Auburn University).

Soil solutions of subsurface horizons of LAC soils contain even fewer electrolytes than solutions of surface horizons. This is probably because of higher organic matter contents and greater microbial activity in surface horizons. Gillman and Bell (1978) found ionic strengths of soil solutions from several subsurface horizons in Queensland, Australia, to range between 0.0002 and 0.002. Adams and Moore (1983) and Adams and Hathcock (1984) examined horizons of several Ultisol profiles in Alabama, United States, to a depth of 1 m and found ionic strengths of soil solutions to range between 0.0004 and 0.012, with most values being <0.003. Furthermore, solution electrolyte concentration decreased with increasing depth in each profile.

Since Schofield and Taylor (1955a) proposed that ion activities of soil solutions be measured in 0.01M $CaCl_2$ soil suspensions, numerous applications of this procedure have been reported. It has been proposed, for example, that this suspension be used to measure pH (Schofield and Taylor 1955b), available P (Aslyng 1954), and available K (Beckett 1964). The basic premise on which these methods are founded assumes that soil solutions have Ca concentrations of approximately 10mM concentration, and ionic strengths equivalent to 10mM $CaCl_2$ (0.03). This premise may be approximately correct for some fertile, alkaline soils, but it is invalid for most LAC soils where both Ca concentrations and ionic strengths are generally lower by a factor of 10 to 100.

Cation Ratios

In normal, fertile soils, the relative concentration of soil solution cations is expected to be Ca > Mg > K. In unfertilized, weathered LAC soils,

however, the relative abundance of these cations is unpredictable. Gillman and Bell (1978), for example, found soil solutions in which the concentrations were K > Mg > Ca, Mg > K > Ca, and even Na > Mg > K > Ca. In those Australian soils, the cation in lowest concentration was usually Ca, particularly in subsurface horizons. In an examination of several Ultisol profiles in Alabama, United States, Adams and Moore (1983) and Adams and Hathcock (1984) found the relative concentration in soil solutions of subsurface horizons in fertilized fields was Ca > Mg > K or Ca > K > Mg, but Ca was lowest of all basic cations in some horizons under unfertilized woodlands. Soil solution compositions of some selected LAC soils are given in Table 7.

Calcium Deficiency

Organic residues and the use of fertilizers and lime make it unlikely that surface soils will be Ca deficient for most crops. Subsurface horizons of some soils, however, may well be prone toward Ca deficiency. Typical candidates for Ca deficiency are the highly leached, acid, sandy horizons of Ultisols and the subsurface horizons of Oxisols. Soil-solution Ca concentration can be very low in some of these. For example, most soil solutions of subsurface horizons sampled by Gillman and Bell (1978) in Queensland, Australia, contained <0.1mM

Table 7. Soil solution composition (Saturation Extracts) of some LAC Soils (A.S.R. Juo and E.J. Kamprath unpublished data).)

LAC Soil	Depth (cm)	Cation (mM)				RCa†
		Ca	Mg	K	Al	
Alfisol	0-16	2.25	2.43	1.17	nil	0.37
(Nigeria)	16-50	0.14	0.05	0.10	nil	0.34
Alfisol	0-15	1.45	7.08	0.44	nil	0.16
(Kenya)	25-65	0.14	0.25	0.03	nil	0.25
Ultisol	0-10	0.08	0.29	0.35	0.10	0.07
(Nigeria)	30-45	0.03	0.04	0.04	0.05	0.08
Ultisol	0-15	0.28	0.14	0.45	0.19	0.22
(Norfolk)	30-80	0.04	0.06	0.33	0.01	0.04
Oxisol	0-28	0.37	0.12	0.86	0.12	0.10
(Venezuala)	45-60	0.05	0.04	0.11	0.01	0.07

† Ca concentration ratio.

Ca and several contained <5μM. Several subsurface horizons of Ultisols sampled by Adams and Moore (1983) and Adams and Hathcock (1984) had soil-solution Ca levels of <0.1mM. Although plant species differ considerably in their root-medium Ca requirements (Loneragan and Snowball 1969), such low Ca concentrations are deficient for many agronomic crops.

As noted by many workers (Clark 1984), Ca concentrations much higher than these can be deficient when micronutrient metals or macronutrient cations are present at normal soil solution concentrations. In experiments with cotton (Gossypium hirsutum L.) roots in low-calcium soils suffered Ca deficiency symptoms when soil-solution Ca was < 0.3-0.4mM (Howard and Adams 1965, Adams and Moore 1983, Adams and Hathcock 1984). Although few soil solutions analyses have been made on horizons of LAC soils, it seems highly probably that subsurface horizons of many Oxisols and Ultisols are Ca deficient for many crops.

Aluminum

LAC soils are usually products of acid weathering, a process that causes the accumulation of the more soluble forms of mineral Al. The solubilities of these Al minerals are highly pH dependent, a property that often leads to toxic Al levels in soil solutions near pH 5 (Adams and Lund 1966; Magistad 1925; Pavan, Bingham, and Pratt 1982). It is unlikely that Al exists as polymers in soil solutions because of the large surface area available for nucleation and crystal growth. Thus, the chemistry of monomeric Al should prevail in soil solutions.

Although some reports suggest that soil-solution Al is present as inorganic monomers (Adams and Lund 1966; Pavan, Bingham, and Pratt 1982), others clearly show that Al in soil solution may also be present as an organo-aluminum complex (Juo 1977, Adams and Hathcock 1984, Adams and Moore 1983). Most attention with organoaluminum complexes in soils has focused on organic matter (Hargrove and Thomas 1982) and humic acids (Ritchie, Posner, and Ritchie 1982). Bloom, McBride, and Weaver (1979) went so far as to conclude that Al at carboxyl sites on organic matter controlled soil-solution Al^{+3} activity at less than pH 5.0.

Soil solutions at low pH may also contain such organic acids as oxalic, malic and citric (Bruckert 1970). There is a strong tendency for these acids to form chelates or ion pairs with Al (Toy, Smith, and Pilbrow 1973; Ng Kee Kwong and Huang 1977). Except for the report by Bruckert (1970), quantitative data on concentrations of these organic acids in soil solutions are nil. Their

presence in soil solutions of some strongly acid Ultisol horizons is strongly suggested by the work of Adams and Hathcock (1984) and Adams and Moore (1983) in which they found relatively high concentrations of Al to be nontoxic to a very Al-sensitive root system. This was observed particularly in E (eluviated) horizons.

For soil-solution Al^{+3} activity to be defined in an acid soil system, it is necessary to distinguish between inorganic Al monomers and Al in the form of organic acid ion pairs. Not being able to make this distinction with currently available methodology was probably the major reason for the dispersion of soil-solution data points in a stability diagram of gibbsite, kaolinite, and Al-hydroxy-interlayered vermiculite (Karathanasis, Adams, and Hajek 1983) for several Ultisols. Mineral transformations in soil profiles will be subjected to improved interpretation and prediction if soil-solution Al can be defined without the interfering effects of soluble organic acids.

Sulfate

The mechanism by which LAC soils control the concentration of soil-solution SO_4^{-2} has not been clearly identified. However, the extent of SO_4^{-2} retention by the solid phase has been correlated with pH (negative), clay content (positive), Fe and Al oxides (positive), and solution SO_4^{2-} concentration (positive) (Aylmore, Karim, and Quirk 1976; Kamprath, Nelson, and Fitts 1956; Kojentajar, Byrnes, and Hellums 1983). In addition, fertilizer P at high rates has been shown to increase solution SO_4^{2-} concentration at constant pH (Adams, Adams, and Odom 1982)

Although most reports emphasize a single mechanism for SO_4^{2-} retention, it seems highly probable that multimechanisms such as ligand exchange (Rajan 1978), precipitation (Adams and Rawajfih 1977), and electrolyte adsorption (Chang and Thomas 1963) are involved. For example, low pH and high SO_4^{2-} favor precipitation of Al-hydroxy-sulfate minerals while pH, where retention is low, might be expected to favor electrolyte adsorption.

Sulfate concentrations in LAC soil solutions vary from as little as 10 mM (Adams and Hathcock 1984) to about 0.3 mM for fertilized, limed soils (Adams, Adams, and Odom 1982). Minimum concentrations of soil-solution SO_4^{2-} needed for maximum growth of plants are yet to be determined for most species. Hue, Adams, and Evans (1984) found that at least 0.25 mM was needed for corn (<u>Zea mays</u> L.) seedlings.

Zinc

The concentration of soil-solution Zn is highly pH dependent. Friesen, Juo, and Miller (1980) reported that Zn concentrations in soil solutions of two Nigerian Ultisols range from about 5 µM at pH 4 to about 0.5 µM at pH 5; Zn concentrations decreased only slightly between pH 5 and 7. Their data showed a drastic change in the Zn-pH relationship at about pH 5.0.

In a similar experiment with two Ultisols in Alabama, Adams, Juo, and Miller (1982) found that soil-solution Zn ranged from 0.15 uM (pH 7.4) to 5.1 µM (pH 4.0). Their data also showed a marked change in the Zn-pH relationship at about pH 5.2.

In each of these experiments, soil-solution Zn exceeded the concentration of 0.1 µM that Carroll and Loneragan (1968) found adequate for plant growth in flowing cultures. There are two probable reasons for this: (1) diffusion in soil failed to renew Zn concentrations at root surfaces as rapidly as in flowing cultures, and (2) Zn was partially present in soil solution as organic complexes which could have been only weakly available to plants.

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PHYSICAL PROPERTIES OF SOILS WITH LOW ACTIVITY CLAYS

R. Lal[1] and D.J. Greenland[2]

Abstract

Tropical Alfisols, Ultisols, and Oxisols are soils with predominantly low activity clays. Together these soil orders cover a vast part of the subhumid and humid tropics. Alfisols and Ultisols have less stable structures than Oxisols. Alfisols and Ultisols have low available water holding capacity, are easily compacted, and, in spite of low soil erodibility, may suffer accelerated soil erosion under the high erosivity of the climate of the humid tropics. Soil physical properties are highly variable. Shallow-rooted seasonal crops suffer from periodic drought stress even in regions of high annual rainfall. If soil erosion is not controlled and physical properties are not maintained at levels favorable to crop production, other inputs are easily wasted. Promising soil management techniques include no-till and mulch farming, agro-forestry, frequent use of leguminous cover crops in the rotation, and mixed cropping systems.

Introduction

The physical properties of soils are fundamentally determined by the forces between the particles of which they are composed and the interaction of these particles with liquid and gaseous phases. Thus, the constitution of the clay fraction is extremely important, as the physicochemical forces between particles are a function of clay constitution. Soil Taxonomy defines "low activity clays" as those with an effective cation exchange capacity (ECEC) of 16 meq per 100 g clay or less, or CEC determined in ammonium acetate of 24 meq per 100 g or less but these values may be revised to 12 to 16, respectively; in practice, this means soils in which the clay fraction is composed predominantly of kaolinite and halloysite, with hydrous oxides of iron and aluminum. These soils are mostly Alfisols, Ultisols, and Oxisols. The Alfisols and Ultisols differ from the Oxisols in that there is a significant clay increase with depth. This difference reflects the fact that at least part of the clay fraction in the oxic Alfisols and Ultisols is readily dispersible, whereas in the Oxisols the clay is highly resistant to dispersion (Table 1). The resistance to dispersion is due to strong interparticle forces, which give rise to stable domains and microaggregates.

[1] Soil Physicist, International Institute for Tropical Agriculture (IITA) Farming Systems Section.

[2] Deputy Director General, International Rice Research Institute (IRRI).

Table 1. Clay aggregation in soils with low activity clays (Ahn 1979).

Soil	Horizon (depth) (cm)	Clay Content Before dispersion (% of soil)	Clay Content After dispersion (% of soil)	Difference	Proportion clay in stable aggregates
More Stable					
Rhodic Paleudult					
or Nitosol	A 11 (5)	20.5	58.4	37.9	0.65
	A 12 (15)	18.9	51.5	32.6	0.63
(Kikuyu friable					
clay, Kenya)	Upper				
	B 2 (30)	4.2	69.8	65.6	0.94
	Lower				
	B 2 (90)	1.8	82.8	81.0	0.98
Alfic Eutrorthox					
(Akamadon Series,	A 11 (5)	7.7	45.2	37.5	0.83
Ghana)	A 12 (13)	7.4	45.2	37.8	0.84
	B 1 (38)	7.2	48.0	40.8	0.85
	B2.1 (80)	11.3	64.7	53.4	0.83
Less Stable					
Plinthic Paleudult					
(Bekwei Series,	A 11 (5)	18.6	19.0	0.4	0.02
Ghana)	A 12 (13)	16.4	20.4	4.0	0.20
	B 21 (30)	19.0	43.2	24.2	0.56
	B 23 (101)	31.9	68.1	36.2	0.53
Plinthic Paleudult					
(Asuansi Series,	A 11 (5)	8.8	12.2	3.4	0.28
Ghana)	A 12 (13)	9.6	12.4	2.8	0.23
	B 1 (28)	10.1	22.2	12.1	0.55
	B2.3 (82)	21.5	49.7	28.2	0.57

The stable aggregation of Oxisols usually persists throughout the soil profile. In the surface soils, microaggregation may be strengthened by the influence of organic materials, so that the soils tend to have good infiltration and water transmission characteristics and a low erodibility. It would be less confusing if this characteristic were essentially confined to the Oxisols, so that it distinguished them from the Alfisols and Ultisols. However, while it often does so, there are some Alfisols and Ultisols that have a similar, very stable aggregation. These normally belong to the Pale-and Rhodic-Great Groups, such as the Rhodic Paleustults formed on basalts in western Nigeria (Moormann 1981) and in Kenya (Ahn 1979). In the FAO system, they belong to the Nitosol Order, or Nitisols that Sombroek and Siderius (1981) have proposed. In earlier terminologies they have been called krasnozems, euchrozems, and reddish brown latosols. As well as the strong to moderate aggregation, they are characterized by a gradual increase in clay content down the profile and cutans in the lower horizons. Often, organic matter content is higher than might be expected for Alfisols and Ultisols in similar environments.

In terms of physical properties, it is possible to recognize two divisions of soils, both with low activity clays, but one with a higher degree of structural stability than the other. The first, with the less stable structure, is composed of Alfisols and Ultisols, with coarse-to medium-textured surface horizons, and a sharp transition to clayey B horizons. The second is composed of the Oxisols and those Alfisols and Ultisols (mostly Rhodic Paleudalf and Rhodic Paleudults) that have only a gradual increase in clay content down the profile, and in the FAO classification belonging to the Nitosols.

Together these soil orders cover a vast part of the subhumid and humid tropics. In Africa, the majority of low activity clay (LAC) soils appear to belong to those with less favorable physical characteristics. Similarly many, though not necessarily the majority, of the LAC soils in South and Southeast Asia belong to this group, whereas in Latin America, and particularly the Amazon basin region with very intense rainfalls, Oxisols (and Nitosols) may be more common. In West Africa, landscapes are generally dominated by Oxic Alfisols and Ultisols wherever rainfall exceeds about 1200 mm per annum (Moormann 1981). In Cameroon, Zaire, and Kenya there may be more than 200 million hectares of Nitosols (or 55 percent of the global total) (Sombroek and Siderius 1982) as well as some Oxisols, particularly in Zaire. In very simple terms it appears that the Oxisols have formed under more intensive weathering conditions. They are often more acid than other LAC soils, and may have

gibbsite and a higher proportion of oxides and hydrous oxides in the clay fraction (Eswaran and Tavernier 1980). The Nitosols are comparable in their higher content of oxides and hydrous oxides. This appears to arise from the parent materials from which they are developed.

Particle Size Distribution

Sedentary uplands in the humid and subhumid tropics have coarse-textured surface horizons often containing as much as 60 to 80 percent sand. The fine fraction has long been eluviated to the clayey subsoil horizon or has been preferentially removed downslope by surface runoff or lateral flow. The existing fine fraction in the surface horizon is primarily due to soil turnover by macrofauna (e.g., termite and earthworm activity). For soils derived from similar parent material, the clay content of the surface horizon generally decreases with an increase in rainfall.

Silanpää (1982) reported on the textural composition of soils of some 30 countries of the tropics and concluded that coarse texture is a typical characteristic of the soils of Zambia, Nigeria, Ghana, Sierra Leone, Malawi, Sri Lanka, India, and Nepal.

Although some soils have a relatively high clay content, they behave like sand because of strong aggregation of clay into sand-size particles (Ahn 1979, Stone and de Silva 1978). That is why field texture evaluation is an important and a useful property (Williams et al. 1983).

Oliveira (1968) surveyed the textural properties of the humid and semiarid (Alfisols) soils of northeast Brazil and reported that the predominant textural classes of these soils were sand, loamy sand, and sandy loam in the semiarid regions; and sandy clay and clay in the humid regions. Pla Sentis (1977) reported that some Alfisols and Ultisols in semiarid and subhumid regions of Venezuela contain as much as 67 to 84 percent sand and only 5 to 14 percent silt. The predominant texture of the uplands of the Los Llanos region of Venezuela was also reported to be sandy to sandy loam (Frómeta et al. 1979). González (1980) reported that upland Colombian soils are nonplastic because of the low clay content and the predominantly low activity clays.

In West Africa, Lévêque (1977) noted that the surface horizon of most uplands lose clay by eluviation. Sedentary soils of West Africa are also characterized by a well-defined gravelly horizon with gravel content ranging from 30 to 80 percent (Table 2) (Lal 1979, Lal 1981). Vine (1954) reported the possible role of macrofauna in the formation of these gravelly horizons. The

Table 2. Gravel contents of different horizons for some soils of Southwest Nigeria (IITA 1975).

Soil Series	Location (coordinates)	Horizons 1	2	3	4	5	6
		------ % gravel content -------					
Egbeda	8°41'N, 3°42'E	5	57	56	54	45	57
Sepeteri	8°41'N, 3°42'E	11	56	69	74	67	39
Iso	8°06'N, 3°20'E	5	34	58	29	18	--
Fashola	8°06'N, 3°20'E	5	39	65	69	72	--
Iwaji	7°51'N, 4°06'E	29	68	72	62	--	--
Erinoke	7°51'N, 4°06'E	0	43	73	63	39	--
Ekiti	7°29'N, 3°53'E	3	7	32	85	88	--
Apomu	8°41'N, 3°42'E	0	0	0	6	12	23

texture of some West African soils occupies the left-hand corner of the textural diagram (Figure 1).

Textural properties of LAC soils of northern Australia are reported by CSIRO (1965) and Northcote et al. (1975). The surface soils have a low clay content, which gradually increases with depth. The predominant texture of the surface horizon is sandy loam and, very rarely, clay loam. Mott, Bridge, and Arndt (1979) analyzed textural properties of some Alfisols in Northern Territory, Australia. These soils contain 12 to 13 percent silt and 55 to 60 percent sand and are susceptible to the formation of a slowly permeable hard crust. Williams et al. (1983) indicated that some soils of tropical Australia contain as little as 4 to 5 percent clay and 6 to 7 percent silt.

From the analyses of Alfisols of the dry zone of Sri Lanka, Joachim and Pandilteskera (1948) reported sand content of 57 to 75 percent in the surface horizon. Alfisols of Central India are similar in textural properties. However, the data of Takahashi et al. (1983) for upland soils of northeast Thailand show a higher silt content in the surface horizon than in soils of the humid and subhumid zone of West and Central Africa.

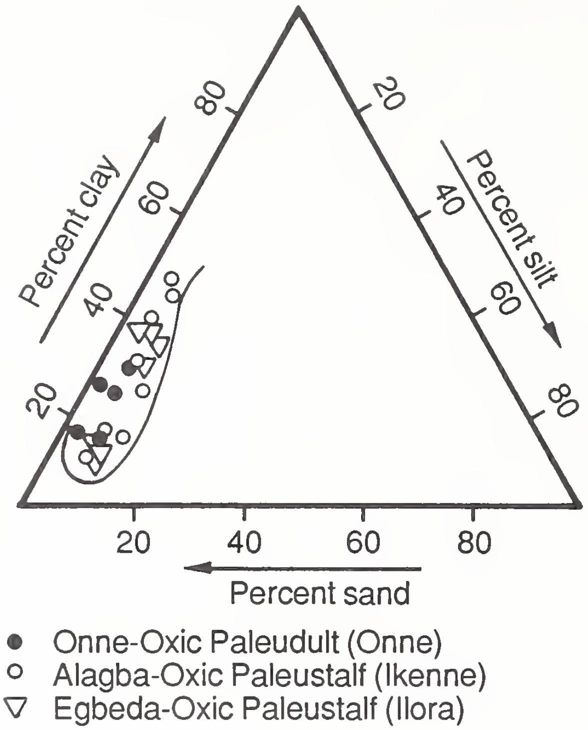

Figure 1. Textural properties of some Nigerian soils (from Mbagwu, Lal, and Scott 1983).

Soil Bulk Density and Mechanical Properties

Much of the early literature on tropical red soils describes their very favorable physical features, combined with inherently poor chemical characterisics. Although the red colors of the subsoils reflect good drainage conditions, differences in structural stability have become apparent. These are reflected in the low bulk densities of the more stable soils which may be below 1 (Table 3); whereas in Oxic Alfisols, values as high as 1.6 to 1.8 have been recorded (Lal 1981).

Depending on the texture and on the activity of soil fauna bulk density of uncultivated soils, the surface horizon of uplands in subhumid and humid regions is generally low. Some uncultivated soils of the savanna and semiarid regions, however, are compacted even prior to their development for arable land use. The latter have a sparse vegetation cover, are exposed unprotected to high intensity monsoons, and are often prone to development of surface seal (Mott, Bridge, and Arndt 1979). Wide variations in soil bulk density are

Table 3. Bulk densities of selected Oxisols and Ultisols (Tanaka *et al*. 1984).

Soil Classification	Horizons			
	A	A3	B	C
	bulk density (g cm^3)			
Typic Haplustox	0.76	0.83	0.85	--
Typic Acrustox	1.25	--	1.24	--
Ultic Haplustox	1.64	1.65	1.52	--
Typic Paleudult	1.37	1.41	1.43	1.65
Aquic Paleudult	1.32	1.47	--	1.56

common phenomena. Soil bulk density and gravel content of two profiles (Table 4) at Hyderabad, Central India, show that these soils, which have been intensively cultivated for centuries, are already compacted. The gravel horizon in these soils is generally deeper than in soils of West Africa.

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Mechanized operations and the frequent traffic of heavy farm machinery rapidly increase soil bulk density (Lal 1984). Once compacted, these soils require prolonged fallowing or drastic mechanical loosening measures, as they have a low shrink-swell-capacity. Cultivated soils in regions with a prolonged dry season are desiccated to a depth of about 1 m. Exposed soils, subjected to

Table 4. Gravel contents and bulk density of two Alfisol profiles at Hyderabad, India (ICRISAT 1978-1979).

Depth	Gravel content (%)		Bulk density (g/cm^3)	
(cm)	ST 2	RA 10	ST 2	RA 10
0 - 15	2.4 ± 0.8	10.9 ± 9.1	1.55 ± 0.22	1.57 ± 0.20
15 - 30	1.5 ± 0.8	7.7 ± 6.0	1.64 ± 0.15	1.72 ± 0.19
30 - 45	0.6 ± 0.8	2.9 ± 1.7	1.59 ± 0.07	1.67 ± 0.10
45 - 60	2.2 ± 4.8	1.4 ± 0.5	1.59 ± 0.12	1.63 ± 0.11
60 - 75	4.3 ± 10.4	2.3 ± 1.3	1.64 ± 0.04	1.71 ± 0.10
75 - 90	5.0 ± 13.0	11.1 ± 19.7	1.60 ± 0.04	1.79 ± 0.12
90 - 105	6.6 ± 10.1	16.2 ± 21.2	1.68 ± 0.10	1.83 ± 0.15
105 - 120	11.2 ± 12.6	30.3 ± 27.8	1.65 ± 0.09	1.85 ± 0.14
120 - 135	12.4 ± 14.5	21.7 ± 18.4	1.75 ± 0.10	1.81 ± 0.16
135 - 150	18.1 ± 17.8	28.3 ± 8.1	1.70 ± 0.09	1.86 ± 0.16
150 - 165	28.0 ± 14.7	33.1 ± 14.1	1.80 ± 0.11	1.86 ± 0.05
165 - 180	30.7 ± 10.0	31.0 ± 15.9	1.74 ± 0.08	1.83 ± 0.13
180 - 195	16.6 ± 14.2	35.1 ± 21.6	1.80 ± 0.14	1.89 ± 0.20

extremes of high temperatures when at low moisture content, develop extremely hard consistencies.

Aggregation and Aggregate Stability

LAC soils with low bulk density often possess stable structures. For example, Oxisols of the Amazon region are more stable than Alfisols and Ultisols of West Africa, Asia, and Northern Australia. The assessment of structural properties is often done through characterization of the relative proportion of macropores 0.1 mm diameter. The higher the proportion of macropores and the lower the bulk density, normally the better the soil structure. Although much of the porosity is due to interparticle separation and high clay content, some is associated with storage and transmission pores, indicating aggregation above the domain level, into microaggregates. The much greater retention of plant-available water in the soils with more stable aggregation (i.e., the presence of a greater proportion of storage pores) is referred to later in the discussion of water retention characteristics. The weaker aggregation at the microaggregate level of the Oxic Alfisols and Ultisols is reflected in a very limited retention of plant-available water.

The stability of domains and microaggregates is shown also by the fact that field textures ascribed to these soils indicate that they are loamy rather than clayey. Even after treatment with hydrogen peroxide and prolonged

shaking, the aggregates of clay-sized material may not be destroyed; the particles separate only after addition of an anionic dispersing agent. This stability is also reflected in the generally low erodibility of these soils, compared with those containing predominantly 2:1 lattice clays (HAC) (El-Swaify 1977). The difference between the more and less stable LAC soils is also shown by their different erodibilities (Table 5). The low soil erodibility values of some LAC soils shown in Table 5, however, do not imply that these soils are less susceptible to soil erosion. The soil erodibility of stable Oxisols is generally lower than that of Alfisols and Ultisols (Table 6).

Origins of Physical Behavior

Koenigs (1961) reported the major differences between the physical properties of soils with clays composed predominantly of kaolinite or halloysite and oxides and hydrous oxides of iron and aluminum (Latosols) and those with clays consisting predominantly of montmorillonite (Margalitic soils). He noted the differences in their ease of dispersion, and the fact that the Margalitic soils were flocculated more readily by solutions of higher electrolyte concentration, in accordance with accepted theory of colloidal

Table 5. Erodibility indices of soils with low activity clays (Lal 1979).

Soil Classification	(Series)	Relative Erodibility Index Soil initially dry	 wet
Less stable			
Oxic Paleustalf	1. (Dongabbe)	0.37	0.07
Oxic Paleustalf	2. (Funtua)	0.57	0.09
Oxic Peleustalf	3. (Egbeda)	0.28	0.06
More stable			
Oxic Paleustalf (and Eutric Nitosol)	4. (Alagba)	0.001	0.001
Typic Paleudult	5. (Onne)	0.001	0.001
Rhodic Paleustult (and Dystric Nitosol)	6. (Itagunmodi)†	0.001	0.001
Orthoxic Tropohumult	7. (Ikom)	0.001	0.001

† In the original publication, this soil was classified as an Oxic Paleustalf. This classification was later corrected (by F.R. Moormann) to Typic Paleudult (see Greenland 1981, p. 402). In the FAO classification, it is a Dystric Nitosol. The Alagba Series was also classified as an Oxic Paleustalf, but in the FAO classification it is a Eutric Nitosol (Greenland 1981, p. 409).

behavior, but the Latosols dispersed more readily in strong electrolytes. He also examined a kaolinite mineral specimen, which behaved normally, and so attributed the anomalous behavior of the Latosols to the influence of the oxides and hydrous oxides of iron.

Much other work has shown the importance of oxides and hydrous oxides of both aluminum and iron to the colloidal behavior of clays. It is now clear that clays may carry a net positive charge, iron oxides up to about pH 7 and aluminum oxides up to about pH 9. Thus, at the pH of many Oxisols and Ultisols, and some Alfisols, they will be quite strongly positively charged, and so promote aggregation of clay minerals with a permanent negative charge. This will include many of the kaolin and halloysite particles occurring with the oxides in the LACs. Also, at a soil pH of 4 to 5 most hydrous oxides of iron and aluminum will be close to their zero point of charge, so that dispersive forces are low.

Koenigs (1961) attributed the dispersion of the Latosol clays by strong electrolytes to the specific adsorption of the anion, rendering the oxide surfaces negatively charged, and so promoting the dispersion of the aggregates.

Table 6. Erodibility of some LAC soils determined on field plots.

Country	Region	Erodibility	Reference
Alfisols			
Benin	Subhumid	0.10	Roose (1977)
Ivory Coast	Subhumid	0.10	Roose (1977)
Kenya	Subhumid	0.03-0.49	Barber, Moore, and Thomas (1979)
Nigeria	Subhumid	0.06-0.36	Lal (1976)
Nigeria	Subhumid	0.058	Wilkinson (1975)
Tanzania	Semiarid	0.121-0.160	Ngatunga, Lal, and Uriyo (1984)
Ultisols			
Hawaii	Humid	0.09	Dangler and El-Swaify (1976)
Nigeria	Humid	0.04	Vanelslande *et al.* (1984)
Thailand	Subhumid	0.09-0.19	Tangtham (1983)
Trinidad	Humid	0.03-0.06	Lindwa and Gumbs (1982)
Oxisols			
Costa Rica	Humid	0.103-0.155	Amezquita and Forsythe (1975)
Hawaii	Humid	0.14-0.22	Dangler and El-Swaify (1976)
Ivory Coast	Humid	0.10	Roose (1977)
Puerto Rico	Humid	0.01	Barnett *et al.* (1971)

This phenomenon has been intensively studied in recent years, and the sorption of phosphate, silicate, and many organic anions is now well understood (Bowden, Posner, and Quirk 1980).

The extent to which the oxide and hydrous oxide surfaces are inactivated through anion adsorption probably determines to a large extent the stability of the structural elements in field soils. Dispersion and translocation of clay in many Alfisols and Ultisols is made possible because silicate or phosphate or organic anions "deactivate" the clay. A smaller proportion of aggregated clay is normally found in the surface horizons of these soils than in the subsoils (Table 1, Bekwai and Asuansi Ultisols) suggesting that organic matter plays an important role in deactivation. Deshpande, Greenland, and Quirk (1968) observed that iron oxides in many red soils had little influence on aggregation or aggregate stability, and attributed this to deactivation of the oxides by anion sorption.

The more active oxides in Nitosols and Oxisols are apparently less subject to deactivation. This may be because the actual amount and surface extent of the oxides are greater, associated with a greater rate of silica removal during soil formation (Gallez, Herbillon, and Juo 1977) and the greater mobilization of aluminum under more acid conditions. Greater stability certainly appears to be associated with the presence of gibbsite. The proportion of aluminum in the lattices of the iron oxides and hydrous oxides may also influence their activity.

While organic anions may have a dispersive effect, due to specific sorption by the oxides and hydrous oxides, organic polymers contribute to the stability of aggregates, most probably through interdomain or intermicro-aggregate bonding. Deshpande, Greenland, and Quirk (1964) showed that there was a major loss of stability of an Ultisol from Katherine, Northern Australia, when polysaccharides were removed by periodate treatment. This loss of stabilization was over and above that induced by sorption of anions arising from the treatment. Stabilization of aggregates by interdomain and microaggregate bonding is almost certainly confined to surface soils.

Thermal Properties

Thermal properties of LAC soils depend on texture and soil organic matter content. The latter declines rapidly with continuous cultivation thereby influencing thermal capacity and conductivity directly. Indirectly, changes in

soil organic matter content influence a soil's thermal properties through their effect on water retention characteristics.

Ghuman and Lal (1985) observed that thermal capacity was different among soils of different mechanical composition (Table 7). In general, clayey soils had higher thermal capacity than sandy soils, probably due to the presence of water film around charged clay particles. Similar results were reported for some arid zone soils of northwest India by Yadav and Saxena (1973). Clayey soils and soils with low bulk density have low thermal conductivity. The data in Figure 2 by Ghuman and Lal (1985) compare the effect of wetness on thermal conductivity of an Alfisol sieved through 1-cm and 0.2-cm sieves with that of a washed sand and an *in situ* measurement of gravelly Alfisol. The data show that for a given wetness, thermal conductivity of washed sand was greater than that of the sieved soil fraction. The *in situ* determined value of thermal conductivity was about 2.5 times lower than that of the 0.2-cm soil fraction. The heterogeneity of the soil profile due to gravels can affect soil thermal properties by several orders of magnitude.

Table 7. Thermal capacity (cal/g °C) of some Nigerian soils (Ghuman and Lal 1985).

Soil	Textural class	Organic carbon content (%)	Air dry wetness (g/g)	Thermal capacity
1	Clay	1.42	0.072	0.324
2	Clay	2.19	0.013	0.248
3	Clay loam	1.56	0.021	0.271
4	Clay loam	2.19	0.014	0.224
5	Loam	1.47	0.011	0.366
6	Loam	1.75	0.002	0.279
7	Sandy clay loam	1.42	0.015	0.350
8	Sandy clay loam	1.75	0.012	0.315
9	Sandy loam	0.39	0.011	0.322
10	Sandy loam	1.79	0.009	0.269

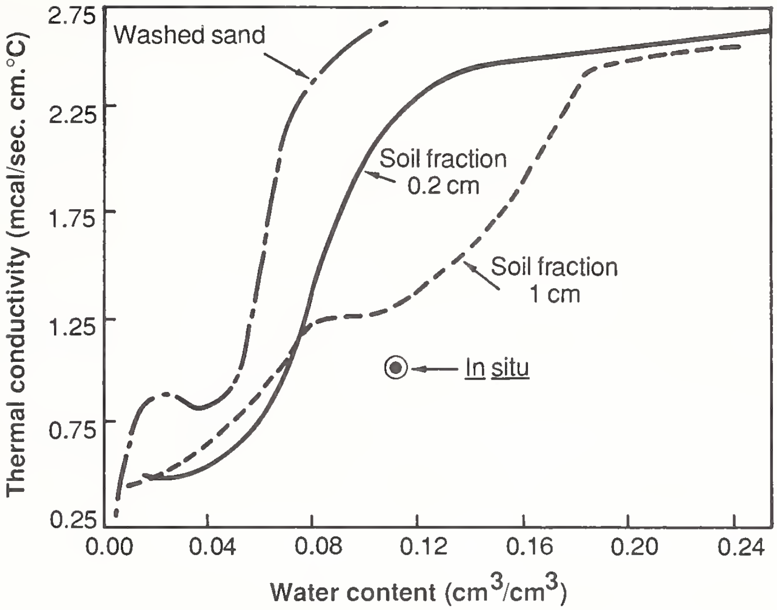

Figure 2. Effect of soil moisture content on thermal conductivity of an Alfisol (Ghuman and Lal 1985).

Soil-Water Retention Properties

Most soils containing low-activity clays are characterized by low available water-holding capacity. This conclusion is based on the data by Kowal (1970), Obi (1974), and Lal (1979) for Nigeria; Arndt, Phillips, and Norman (1963), Graaff (1965), and McCown (1979) for tropical Australia; Selvakumari, Raj, and Krishnamorthy (1973), Banerjee and Chand (1981), and Oswal and Khanna (1981) for soils of south Asia; Pla Sentis (1977), Roeder and Bornemisza (1968), and Tanaka et al. (1984) for soils of tropical America. The water-holding capacity of the rooting zone is often as low as 2 to 5 cm available water reserves. Consequently, seasonal crops are prone to periodic drought stress throughout the growing season if a rainless period exceeds 7 to 10 days.

Because the soil is either coarse-textured or behaves as if it were, the upper limit of available water content (field capacity) is often attained at low soil-water suction. In fact, the equilibrium moisture content corresponding to the field moisture capacity is attained within 24 hours after being saturated, with little subsequent change in the water content. For example, for soils of southwest Nigeria, Amezquita (1981) reported equilibrium moisture content of the surface soil ranging from 12 to 29 percent with a

corresponding suction value of 25 to 50 cm of water. Bonsu and Lal (1983) observed field moisture capacity between 50 and 90 cm of water suction. Kowal and Kassam (1978) observed that the suction corresponding to field moisture capacity of some sedentary soils of West African savanna ranges from 0.08 to 0.125 bar of water.

Soil moisture retention characteristics are such that most of the available water is released at low suction, 0.3 to 0.5 bar. The available water reserve beyond a suction of about 1.0 bar is often small and there is little difference in moisture retained at 1 and 15 bar suctions (Figure 3). Mott, Bridge, and Arndt (1979) reported that the available water reserve of some soils of Northern Territory, Australia, is only 10 to 12 percent and most of it is released below 1 bar suction. In Venezuela, Pla Sentis (1977) reported that the soils of the Guanipa series retain 7.5, 5.0, and 2.0 percent moisture at suctions of 0.1, 2.0, and 15.0 bar, respectively, with most of the available water being released at suctions of less than 0.3 bar (Figure 4). In Brazil, Roeder and Bornemisza (1968) reported that soils retain 20 to 30 percent moisture at 0.3 bar suction and only 8 to 10 percent at 0.5 bar suction. Similar observations were made by Wolf and Drosdoff (1976) and Escolar and Lugo Lopez (1969) for soils of Puerto Rico.

There are drastic differences in soil moisture retention properties determined in situ and those measured in the laboratory even on undisturbed cores. The laboratory determined pF curves often indicate higher moisture retention than those measured in situ (Bonsu and Lal 1983, Kyuma and Pairintra 1983). One of the problems of assessing soil moisture constants (i.e., field moisture capacity and the permanent wilting point) is that they are dynamic entities. The so-called field moisture capacity is a tentative value because the profile drainage seldom ceases. The lower limit of available water content or the permanent wilting point also depends on crop, evapotranspiration, microclimate, and the management system. Obi (1974) and Amezquita (1981) and others have observed differences among crops in the moisture content at the permanent wilting point.

Water Transmission Properties

Uncultivated uplands are freely drained with high infiltration rates. In general, the soils of the savanna and semiarid regions with low vegetation cover have lower infiltration rates than those within the forest ecology. With

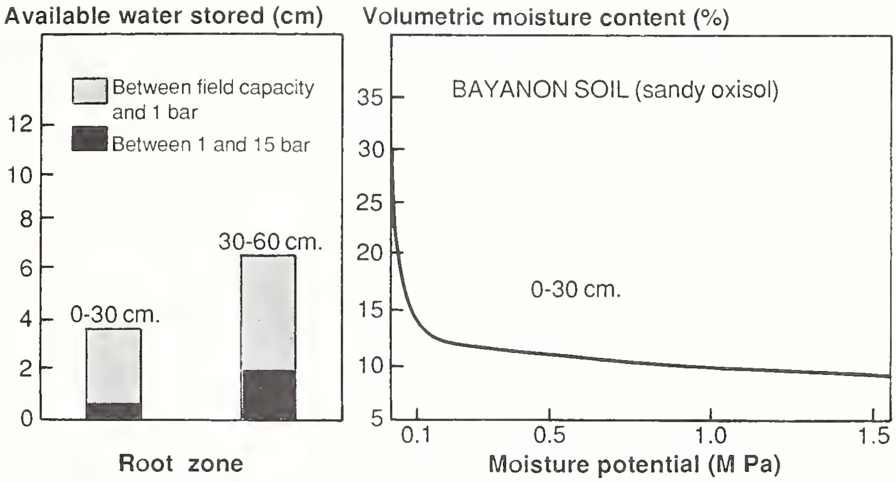

Figure 3. The available water retention properties of some LAC soils of Puerto Rico (Wolf and Drosdof 1976a,b).

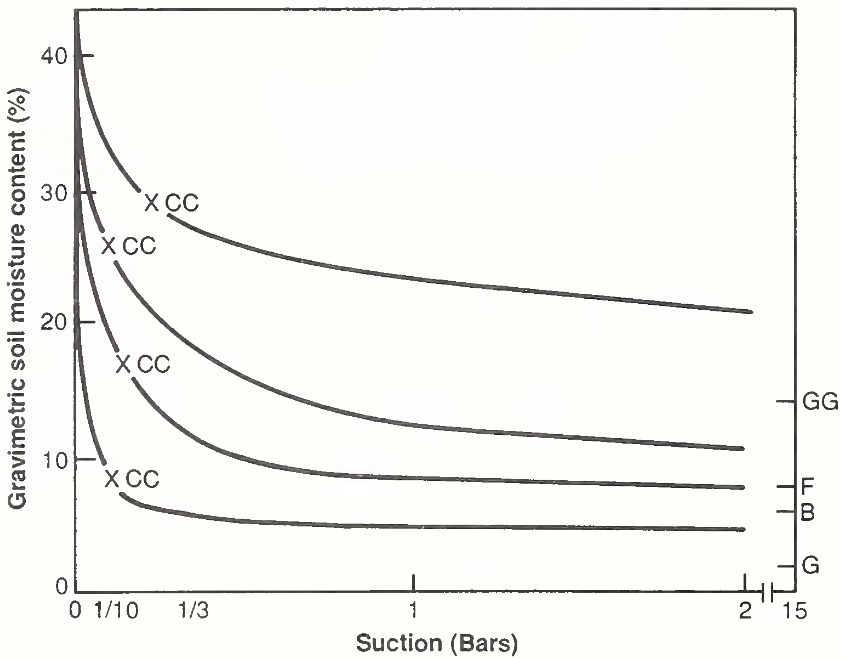

Figure 4. Soil moisture retention characteristics of some LAC soils from Venezuela (after Pla Sentis 1977).

cultivation, however, the infiltration rate declines rapidly, because these soils are easily compacted, and, because of low structural stability, develop surface seals and crusts that render them nearly impermeable.

Water infiltration

That the uncultivated soils of the humid and subhumid tropics have high infiltration rates has been demonstrated for a wide range of soils. High infiltration rate is attributed to macropores created by biotic activity. Strongly developed microaggregates of clayey soils also permit an infiltration rate similar to or in excess of that for the coarse-textured soils. High rates of infiltration on sloping lands are also due to lateral water movement downslope.

For example Wilkinson and Aina (1976) and Moormann, Lal, and Juo (1975) observed the infiltration rate of soils of the forest zone in southern Nigeria to be high. These conclusions are also supported by the data of Mbagwu, Lal, and Scott (1983). The high water intake rates of some soils of Cuba have been related to their physical and mechanical properties (Simeon 1979, Sagué Diaz et al. 1979). Wolf and Drosdoff (1976a) reported very rapid infiltration into clayey Ultisols, clayey Oxisols, and a sandy Oxisol in Puerto Rico.

Infiltration rates decline rapidly with cultivation. For example, Lal (1985) observed that on watersheds growing maize with mechanized farm operations the infiltration rate declined from 71 cm hr^{-1} in the first year of cultivation in 1976 to 33 cm hr^{-1} in 1978, 18.5 cm hr^{-1} in 1979, and 8.5 cm hr^{-1} in 1980. The rate of decline, however, differs among tillage methods (Figure 5). This drastic decline in infiltration rate indicates structural collapse and elimination of transmission pores as a result of vehicle traffic and soil compaction. Similar observations were made by Wilkinson and Aina (1976). The low infiltration rate of some Alfisols of central India (ICRISAT 1975-1976) is also due to the prolonged period of cultivation of these soils and absence of fauna. The equilibrium infiltration rates of these soils are hardly 1 to 2 cm hr^{-1}. In Thailand, Bridge, Sarmnum, and Aromratria (1975) attributed low infiltration rates of some uplands to susceptibility to crusting. However, high infiltration rates can be restored by fallowing with deep-rooted grass or legume covers. Lal, Wilson, and Okigbo (1979) observed significant increases in infiltration rates by 2 years of growing cover crops. Well-established sown pastures usually increase macropore space and improve infiltration rate and soil water sorptivity (Bridge et al. 1983).

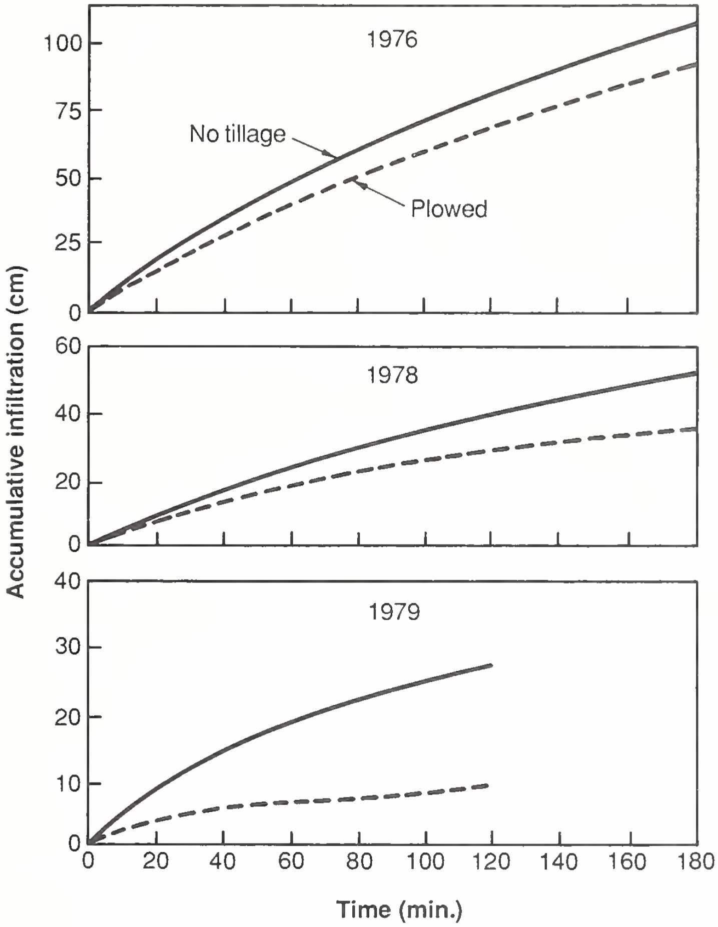

Figure 5. Effects of tillage methods and duration of cultivation on water infiltration rate of an Alfisol in western Nigeria (Lal 1985).

Hydraulic conductivity

Soils with high infiltration rates have naturally high saturated hydraulic conductivity. Bridge et al. (1983) reported the saturated hydraulic conductivity of soils of the dry savanna woodlands of Northern Australia to range from 1.5 to 10.92 cm hr^{-1}. The unsaturated hydraulic conductivity, however, declines rapidly with decrease in soil moisture potential (Amezquita 1981, Bonsu and Lal 1983, Stone and de Silva 1978).

Aeration

Most sedentary uplands are well drained and have good air capacity even at low soil-water potentials. Soil air has not been extensively studied in the tropics. Some biologists have reported the evolution of CO_2 in different

ecologies in relation to biotic activity and the decomposition rate of leaf litter and biomass. Lal (1984) studied the oxygen diffusion rate (ODR) in cultivated uplands and observed that gaseous exchange was not a constraint if the surface soil was not disturbed and was kept mulched (Table 8). The ODR values are generally low for soils and management systems that render surface soil prone to crusting (i.e., plowing without mulch). Soils high in silt content and low in organic matter and those that are exposed to raindrop impact have low ODR. In general, sedentary uplands have well-drained profiles and desirable levels of aeration capacity.

Variability in Physical Properties of LAC Soils

Physical properties of LAC soils are often more variable than chemical properties. This is particularly so for soils either under shifting cultivation or those that have just been cleared of a fallow vegetation. This differential variability may partly be due to the methodology used. Most soil physical properties are determined in situ (i.e., infiltration, bulk density, pF curves, etc.). In contrast, soil chemical properties are determined on relatively small samples that have been sieved through a 2-mm sieve.

Variability in textural and mechanical properties of surface soils are largely associated with different concentrations of gravel and skeletal materials. Babalola (1978) observed coefficients of variation of sand, silt, and clay content on a 91.6 ha farm near Ibadan, Nigeria, of 3.2, 16.5, and 34.0 percent for 0-15 cm depth; and 5.1, 28.5, and 39.9 percent for 15-45 cm depth.

Table 8. The oxygen diffusion rate of an Alfisol with and without crop residue mulch (unpublished data, Lal 1984).

Treatment	Oxygen diffusion rate			
	I	II	III	II
No-till with mulch	0.516	0.652	0.722	0.682
No-till without mulch	0.441	0.630	0.720	0.665
Plowed with mulch	0.568	0.629	0.703	0.666
Plowed without mulch	0.458	0.604	0.637	0.653

The corresponding coefficients of variation for gravel content were 10 and 90 percent, respectively. Lal (1985) reported high variations in gravel content, bulk density, and penetrometer resistance of the surface soil of a 5-ha watershed.

Variability in gravimetric measurements of soil moisture content is often more than in situ assessment of soil moisture potential (Babalola 1978). In many soils, the determination of soil moisture content by the neutron probe method is erroneous because of the high variability in texture and gravel content of the subsoil horizon (Lal 1979). Spatial variability in hydrological properties is often more pronounced and striking than in textural and mechanical properties. This is because a slight variation in textural and mechanical properties results in variability in hydrological properties by several orders of magnitude. Apparently uniform areas exhibit large variability in infiltration rate, hydraulic conductivity, and in the magnitude of the runoff generated. Lal (1984) reported that for 5 ha watersheds, the coefficient of variability of runoff ranged from 16 to 40 percent and of soil erosion from 23 to 69 percent.

This high microvariability is attributed to differences in the parent material and its stage of weathering (Van Wambeke and Dudal 1978), to pedological factors and lithological discontinuities (Moormann and Kang 1978), to diversity of tree species and vegetation cover (Kang 1977; Dancette and Poulain 1968; McCown, Murtha, and Field 1977), to the activity of soil fauna (Kang and Moormann 1977, Hole 1981), to slope and microrelief (Leite and Ezeta 1982) and to man's activity (e.g., fire, deforestation, tillage methods, etc.).

It is important to understand the sources of variability and develop methods of sampling and analyses in view of the factors affecting this variability. The optimum number of samples required should be determined by Krieging.

Implications to Management

The soil physical characteristics of Alfisols, Ultisols, and Oxisols described are constraints to intensive utilization for seasonal crop production. The use of conventional technology based on mechanized tillage operations and intensive use of chemicals has often caused spectacular and costly failures, disappointments, and disillusions. These soils are easily compacted, are susceptible to drought and supraoptimal soil temperatures, and are prone to accelerated soil erosion. In spite of heavy rains, crops suffer

from drought because the water storage capacity of most of these soils is low. Intensive utilization of these soils for food crop production is possible only if soil and crop management systems are available to overcome these problems. This is achievable provided that the delicate soil-vegetation-climate equilibrium is not drastically disturbed, the soil is continuously covered while the crops are grown, biological activity of soil fauna is preserved to provide a natural soil-turnover mechanism, and deep-rooted cover crops and woody perennials are included in the rotation to loosen the subsoil and to provide a nutrient-recycling mechanism.

Because these soils are easily compacted and eroded, it is important to avoid the use of heavy farm machinery. Soil surface management practices are crucial toward achieving this objective. For example, maintaining a layer of crop residue mulch on the soil surface is a particularly valuable means of maintaining the soil's capacity to accept high intensity rains (Lal 1976; Khatibu, Lal, and Jana 1984). Practical methods of procuring mulch include the previous crop residue, specially planted cover crops, and seeding by the no-till system. In addition to preventing erosion, the no-till method has been demonstrated to create favorable soil temperature and soil moisture regimes, enhance activity of soil fauna, and improve soil structure (Lal 1983). The frequent use of cover crops is required to provide ground cover quickly and to protect steep slopes from accelerated soil erosion (Wilson, Lal, and Okigbo 1982). Growing seasonal crops in association with woody perennials by a method of "alley cropping" is also a promising system to meet diverse needs (Kang, Wilson, and Sipkens 1981).

Experiments conducted at IITA and elsewhere in the tropics (Sanchez and Salinas 1981, Lal 1983) have shown that with the adoption of the techniques described, high and economic productivity from these soils is achievable. Most LAC soils can be intensively cultivated and can produce high levels of economic yields without severe degradation of soils and environments.

Conclusions

Low activity clay soils comprising Alfisols, Ultisols, and Oxisols cover large parts of the humid and subhumid tropics. These soils are characterized by either coarse-textured surface horizons or those that behave in the same manner because the clay is often aggregated into sand- or silt-sized stable microaggregates. In general, Alfisols and Ultisols have a lower degree of structural stability than Oxisols because the latter are formed under more

intensive weathering conditions. More stable Oxisols are porous, with low bulk density, whereas high bulk density is often observed in easily compacted Alfisols and Ultisols. The erodibility of Oxisols is also lower than that of Alfisols and Ultisols. In West Africa, the majority of LAC soils derived from basement complex rocks contain a distinct gravelly horizon of varying thickness and concentration. The porosity associated with macrotransmission is responsible for high infiltration rates. High initial infiltration rates, however, decline rapidly with cultivation especially in the case of structurally unstable Alfisols. Field moisture capacity is often attained at 25 to 60 cm water suction and most of the available water is released below 1 bar of suction. The available water holding capacity of these soils is low.

The physical properties of LAC soils are highly variable. Attempts should be made to identify the sources of variability and to obtain an adequate number of samples for representative analyses. These soils can be managed to produce high and economic yields provided those soil surface management techniques are adopted that cause minimal soil disturbance and maintain residue mulch. Alley cropping and frequent use of grass-legume cover crops have been shown to maintain high yields while minimizing the risks of soil erosion, compaction, and degradation.

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FERTILITY MANAGEMENT OF LOW ACTIVITY CLAY SOILS

E.J. Kamprath

Introduction

Soils in which the clay fraction is primarily low activity clays are--in their natural state--acid and infertile. With liming and fertilization, however, these soils can be very productive. Initially, when soils with low activity clays were brought under intensive agriculture, the practices of liming and fertilization which are successful with soils having high activity clays often ended in failure. Research studies over the past four decades with soils of southeastern United States and those of subtropical and tropical areas have provided the framework for developing sound liming and fertilization programs.

Liming

Soils with low activity clays are inherently acid and contain very small amounts of exchangeable Ca and Mg. A major advance in our understanding of soil acidity was made when soil chemists reestablished, in the early 1950s, that exchangeable Al was the predominant cation in acid soils rather than exchangeable H (Coleman and Thomas 1967). It was also shown that the cation-exchange capacity (CEC) of low activity clays has a very large pH-dependent charge (Coleman, Weedy, and McCracken 1959). Coleman suggested that when the base saturation of a soil was based on the CEC determined by the sum of exchangeable bases plus KCl-exchangeable Al (effective cation-exchange capacity), a more realistic evaluation would be obtained of the actual base saturation that plants were experiencing.

Ultisols and Oxisols, which are acid in reaction (<pH 5), have a high Al saturation of the effective cation-exchange capacity (ECEC) and a relatively high concentration of Al in the soil solution (Table 1). Acid soils are also generally low in available Ca and Mg. Direct responses to liming of acid soils are due to neutralization of the toxic ions Al, H, and Mn, and supplying of Ca and Mg. Liming to reduce Al saturation to very low levels will raise the soil pH to sufficient levels that the H ion concentration is no longer detrimental and Mn concentrations are reduced to nontoxic levels. Based on these

[1] Professor at North Carolina State University, School of Agriculture and Life Sciences, Department of Soil Science, Box 7619, Raleigh, NC 27695-7619.

Table 1. Exchangeable Al^{3+} and Ca^{2+} and soil solution Al and Ca of low activity clay soils.

Area	Soil	pH	Exchangeable Ca^{+2}	Exchangeable Al^{+3}	ECEC	Saturation Ca	Saturation Al	Soil Solution Ca	Soil Solution Al
			$cmol(p^+)kg^{-1}$			---%----		$mmol(p^+)L^{-1}$	
North Carolina*	Paleudult	4.6	1.00	3.67	4.77	23	77	5.0	0.55
Nigeria†	Paleudult	4.2	0.26	1.83	2.86	9	64	--	0.30
Alabama‡	Paleudult	4.4	--	1.23	2.73	--	45	18.6	0.44
Brazil§	Haplustox	4.5	0.45	1.15	1.64	26	70	1.14	0.16

* Evans and Kamprath 1970.
† Juo 1977.
‡ Pearson *et al*. 1977.
§ Gonzalez-Erico *et al*. 1979.

considerations, the percentage of ECEC saturated with exchangeable Al was proposed as the criterion for liming of a mineral soil (Kamprath 1970). Crop growth on Ultisols and Oxisols with greater than 60 percent Al saturation was less than 50 percent that of the limed soils (Kamprath 1984).

The relative yield of corn on three Ultisols was a function of the Al saturation of the ECEC (Figure 1). Grain yield was greater than 90 percent of maximum when Al saturations were less than 20 percent. Liming to raise the pH beyond that at which Al saturation was reduced to zero did not give further increases in grain yield (Fox 1979). Grain yields were drastically decreased at Al saturations greater than 60 percent. Concentration of Al in the soil solution increased sharply in surface horizons of Ultisols when Al saturation was greater than 60 percent (Evans and Kamprath 1970). Soybean yields on Oxisols were sharply reduced at Al saturations greater than 10 percent (Figure 2). Soybean, a legume and dependent upon N fixation, is more sensitive to Al than corn, a nonlegume. Nodule numbers per soybean increased from 12/plant at 81 percent Al saturation to 38/plant at 4 percent Al saturation (Sartain and Kamprath 1975).

Depth of liming is an important factor in increasing utilization of subsoil moisture. Root growth of corn in the 15 to 30 cm depth of an Oxisol

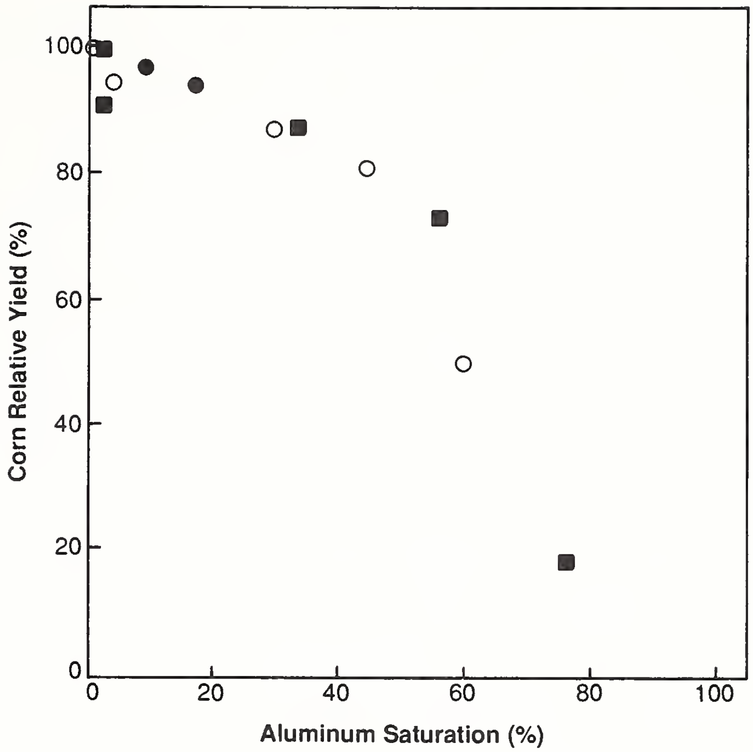

Figure 1. Relative yield of corn as related to percent aluminum saturation of CEC of three Ultisols (Fox 1979, Alley 1981).

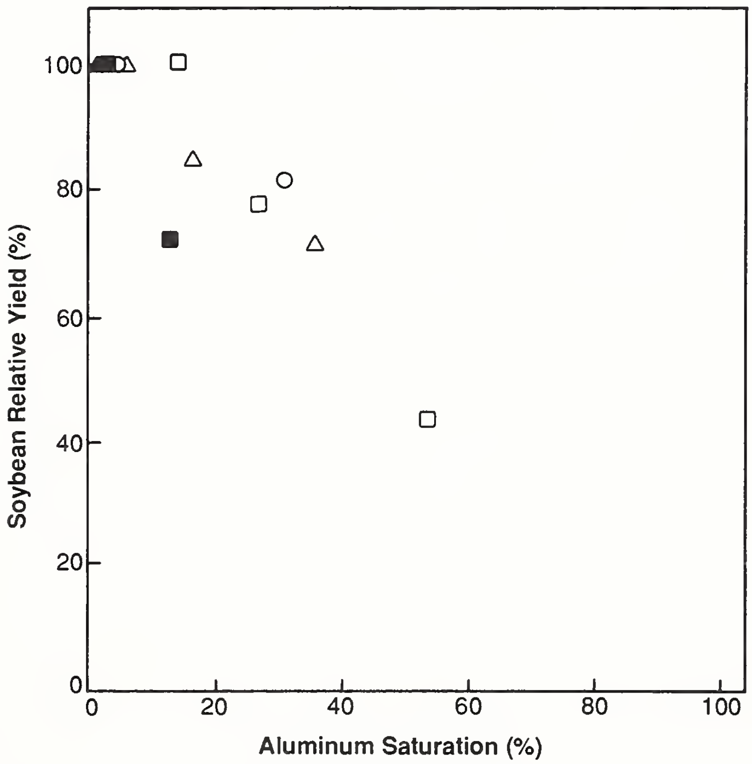

Figure 2. Relative yield of soybeans as related to percent aluminum saturation of three Oxisols (Martini etal. 1974).

was doubled when the Al saturation was decreased from 75 percent to 5 percent (Gonzalez-Erico et al. 1979). The increased root growth resulted in greater utilization of soil moisture in the 15 to 30 cm depth and higher grain yield.

The Ca content in the subsoil of an Oxisol was increased and exchangeable Al was decreased with the application of 9700 kg ha^{-1} of ordinary superphosphate (Ritchey et al. 1980). The $CaSO_4 \cdot 2H_2O$ present in the ordinary superphosphate moved with the sulfate ions to the lower soil depths. Application of lime without the ordinary superphosphate did not result in an increase of Ca in the subsoil. Roots of corn grew into the subsoil on the plots which had received the ordinary superphosphate. Thus, in soils with primary kaolinite-iron oxide mineralogy, the addition of $CaSO_4 \cdot 2H_2O$ and subsequent leaching of Ca improves the base status of the subsoil.

The amount of exchangeable Al can be used as the criterion to determine the amount of lime to apply to acid soils (Kamprath 1970). The amount of $CaCO_3$ required to neutralize a specific quantity of KCl-exchangeable Al is given by the equation (Kamprath 1984):

$$CaCO_3 \text{ tons ha}^{-1} = \text{cmole}(1/3\ Al^{-3})\text{kg}^{-1} \times \text{factor.}$$

The factor for most Ultisols and Oxisols is in the range of 1.5 to 2. The factor takes into account that as the pH of the soils increases, pH-dependent acidity ionizes and reacts with lime. The amount of $CaCO_3$ calculated by the equation (1) using a factor of 1.5 to 2 will reduce the Al saturation to approximately zero and supply adequate Ca. Where Mg levels are low, dolomite lime should be used to supply both Ca and Mg. Maintaining an exchangeable Mg saturation of 4 percent provided adequate Mg for crops grown on Ultisols (Adams and Henderson 1962).

Phosphorus

Ultisols and Oxisols have very low amounts of native available soil P. Without the addition of fertilizer P, crop growth is severely limited. Phosphate applied to LAC soils readily reacts with the Fe and Al oxides to form reaction products which are sparingly soluble. In highly weathered soils, it was found that clay content and organic matter content were associated with the relative P sorbing index of the soil (Sharpley et al. 1984). The reasons for these relationships are that the contents of these Fe and Al oxides in LAC soils increases with increasing clay content, and Al and Fe ions counter the negative charge of organic matter. Thus, the amount of fertilizer P that has

to be added to give a certain level of available P is a function of soil texture. Much higher amounts of fertilizer P have to be added to clayey soils than to sandy soils to increase soil test levels (Figure 3).

One approach in P fertilization of LAC soils is to broadcast a sufficient quantity of P fertilizer to bring the soil test to or above the critical level. The amount to add will be a function of the soil texture. With an experiment on a sandy loam soil (Typic Hapludult), a broadcast application rate of P at 128 kg ha^{-1} gave the maximum yield of soybeans (Table 2). The rate of P at 128 kg ha^{-1} maintained an adequate P supply for 4 years of a wheat-soybean cropping system (Sharpe et al. 1984). Another study with a sandy loam (Typic Hapludult) found that broadcast application of P at 140 kg ha^{-1} gave corn yields that were 90 percent of the maximum (Alley and Bertsch 1983). Higher rates of P were required on a clayey Oxisol in Brazil for maximum yields of corn (Table 3). A broadcast application of P at 560 kg ha^{-1} gave a higher yield than 280 kg ha^{-1} which yielded 85 percent of the maximum. The 560 kg ha^{-1} rate continued to supply adequate P through four crops. There was a sharp drop, however, in the yields of 70 and 140 kg ha^{-1} P treatments, indicating a sharp drop in the availability of P by the fourth crop as compared with the first crop.

With high P sorbing soils, an alternative approach is to initially broadcast a moderate rate of P and then apply a band application with each crop. An initial broadcast application of P 140 kg ha^{-1} and a band application of 35 kg ha^{-1} to each crop resulted in 80 to 85 percent of the yield obtained with the high broadcast rate (Figure 4). When only a band application of P 35 kg ha^{-1} was applied, yields did not approach that of the combination of broadcast and band treatments until the third crop. An initial broadcast application of P 170 kg ha^{-1} and annual applications of 25 kg ha^{-1} gave corn yields of 88 percent of that obtained with an initial broadcast of 685 kg ha^{-1} 8 years earlier (Kamprath 1967).

There is a considerable residual effect from large applications of P fertilizer to high P sorbing soils. Application of P 685 kg ha^{-1} to a red Piedmont, Typic Hapludult 9 years earlier supplied adequate P for high corn yields (Kamprath 1967).

Soil tests can be used to identify the soils which contain adequate supplies of soil P and those which are deficient. Soil test values at which little or no response to P fertilization are expected are shown in Table 4. Critical values of double-acid (HCl + H_2SO_4) P for clayey textured soils

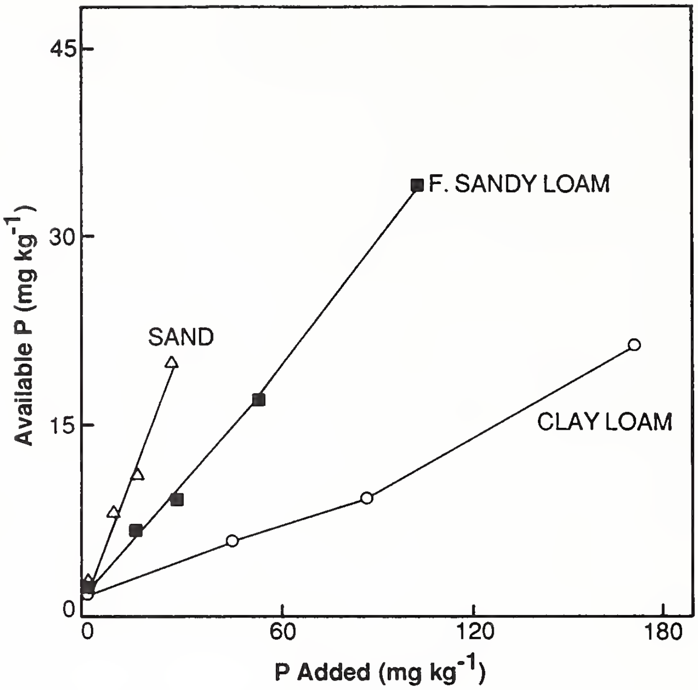

Figure 3. Effect of texture on the amount of fertilizer phosphorus required on Ultisols to give various levels of double acid extractable P (Woodruff 1963).

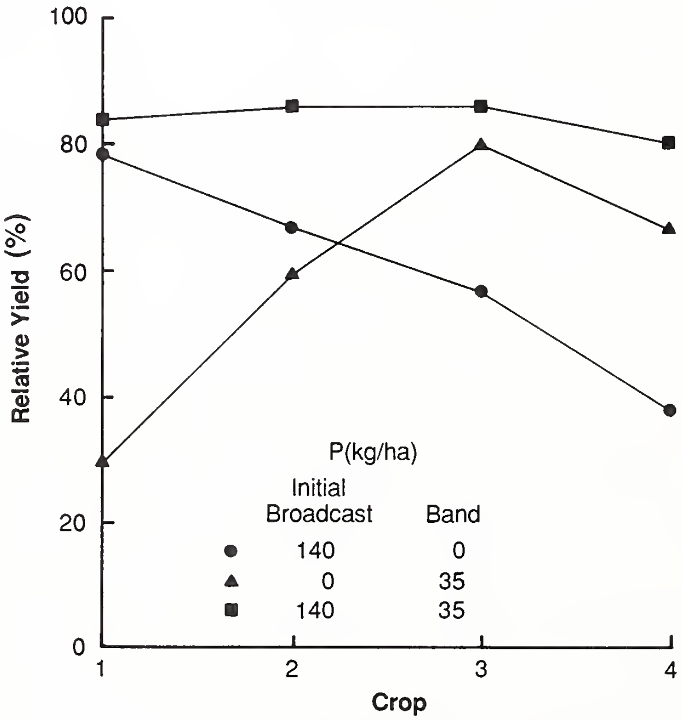

Figure 4. Relative yield of corn as influenced by rate and method of P application. Broadcast P applied to first crop and band application to each crop. Reference yield was 560 kg ha^{-1} applied broadcast to first crop. (Data from Yost et al. 1979)

Table 2. Response of soybeans to fertilizer P applied to a Hapludult (data from Sharpe *et al*. 1984).

Fertilizer P ($kg\ ha^{-1}$)	Soil test P ($mg\ kg^{-1}$)	Soybean yield ($tons\ ha^{-1}$)
0	0	2.30
64	10	2.70
128	25	3.15
256	48	3.10
384	100	3.10

Table 3. Response of corn to P fertilization of a Typic Haplustox in Brazil (data from Yost *et al*. 1979).

P Treatment*	Corn Grain ($tons\ ha^{-1}$)	
($kg\ ha^{-1}$)	Crop I	Crop IV
Broadcast 70	5.23	1.78
Broadcast 140	6.27	3/42
Broadcast 280	6.79	6.42
Broadcast 560	7.96	9.09
Broadcast 140 + 35 Band	6.65	7.22
Band 35	4.56	6.03

* Broadcast P fertilizers applied only once before planting of the first crop while band applications were made for each crop.

Table 4. Critical soil test values for extractable P as related to soil texture.

Soil	Texture	Crop	Extractant	Critical value (ug g^{-1})
Typic Hapludult*	sandy loam	corn	0.05N HCl + 0.025N H_2SO_4	33
			Bray 1	36
			0.5M $NaHCO_3$	18
Typic Hapludult†	clay loam	corn	0.05N HCl + 0.025N H_2SO_4	10
Typic Haplustox‡	clay	corn	0.05N HCl + 0.025N H_2SO_4	10-15
			0.5M $NaHCO_3$	6-10
Typic Hapludult§	sandy loam	wheat	0.05N HCl + 0.025N H_2SO_4	27
		soybean	0.05N HCl + 0.025N H_2SO_4	30

* Alley and Bertsch 1983.
† Kamprath 1967.
‡ Yost *et al*. 1979.
§ Hargrove, Boswell, and Touchton 1984.

are in the range of P 10 to 15 µg g^{-1} soil, while for the sandy soils the values are P 25 to 30 µg g^{-1} soil. Critical values for the $NaHCO_3$ method were approximately half that of the double acid. The differences in critical levels for clayey soils *vs* sandy soils are due to differences in buffering capacity of the soils. To increase the double-acid (HCl + H_2SO_4) soil test P on µg g^{-1} soil, the amounts of fertilizer P were 5 to 6 kg ha^{-1} on sandy loam soil and P 12 kg ha^{-1} on clayey soils (Rouse 1968).

The efficiency of fertilizer P and soil P is increased when soils with a high Al saturation are limed. Optimum wheat yields on an Oxisol were obtained at much lower soil test P levels when the Al saturation was reduced to zero by liming (de Magalhaes, Lobato, and Rodrigues 1980). Friesen, Miller, and Juo (1980) found that increased P uptake when exchangeable Al was neutralized

correlated with increased root growth in a Ultisol. Neutralization of Al increased the effectiveness of a given rate of fertilizer P in increasing plant growth on Oxisols (Mendez and Kamprath 1978). When Al was not present, liming had no beneficial effect on increasing the efficiency of P fertilizers. (1980) found that increased P uptake when exchangeable Al was neutralized was correlated with increased root growth in an Ultisol. Neutralization of Al increased the effectiveness of a given rate of fertilizer P in increasing plant growth on Oxisols (Mendez and Kamprath 1978). When Al was not present, liming had no beneficial effect on increasing the efficiency of P fertilizers.

Potassium

Soils that have been subjected to intensive leaching generally have low levels of labile potassium (Graham and Fox 1971). Boyer (1972) reported that tropical areas, K deficiency symptoms are often found when exchangeable K levels are less than 0.10 cmol(p+)kg^{-1}. However, very little response to K fertilization has been obtained when exchangeable K levels are greater than 0.20 to 0.30 cmol(p+)kg^{-1} (de Frietas, McClung, and Gomes 1966). On these same soils very little response was obtained to K fertilization when K levels were greater than 0.30 cmol(p+)kg^{-1}. Application of 83 kg K ha^{-1} gave a significant increase in corn grain on a Plinthic Paleudult with 0.07cmol(p+) kg^{-1} of exchangeable K (Table 5).

The level to which exchangeable K can be built up depends upon the CEC of the soil. Exchangeable K levels were increased on a soil with a CEC of 6 cmol (p+)kg^{-1} by application of K at 33 kg ha^{-1} but not on a soil with a CEC of 3 cmol(p+)kg^{-1} (Table 6).

Potassium when applied at high rates to low CEC soils is readily leached particularly in coarse-textured soils. Potassium levels in the Ap horizon of a Paleudult reached an equilibrium 5 months after application of K fertilizers (Table 7). Exchangeable K levels resulting from application rates of K at 83 and 249 kg ha^{-1} were not much different 12 months after the K was applied, indicating that at the high K rates a large amount of K had leached. Thus, on these soils with low CEC, K fertilization practices should be based on the K requirements of the crop and maintenance of K levels in the range of 0.1 to 0.15 cmol(p+)kg^{-1}.

Potassium leached from Ap horizons can be retained in the B horizon. Application of K 180 kg ha^{-1} for a period of 4 years resulted in an appreciable accumulation of K in the B horizon of a Typic Paleudult (Woodruff

Table 5. Effect of K fertilization on corn yield on a Paleudult with 0.07 cmol K^+ kg^{-1}.

K ($kg\ ha^{-1}$)	Corn grain ($tons\ ha^{-1}$)
0	6.43
83	8.38

(Source: Sparks, Martens, and Zelazny 1980)

Table 6. Effect of CEC on the soil test K values resulting from annual applications of K (data from Cope 1983).

Soil Test K ($kg\ ha^{-1}$)	Typic Paleudult	Typic Hapludult
	---------- (cmol(+) kg^{-1}) ----------	
Initial	0.10	0.14
Annual		
0	0.09	0.15
33	0.11	0.21
50	0.12	0.25

Table 7. Effect of K rates on exchangeable K Levels of the Ap Horizon of a Paleudult at various times after application.

	Months After K Application			
Fertilizer K ($kg\ ha^{-1}$)	3	5	8	12
	------------- Exchangeable K, cmol(p^+)kg^{-1} -------------			
0	0.09	0.07	0.08	0.07
83	0.12	0.09	0.09	0.11
249	0.19	0.13	0.12	0.12

(Source: Sparks, Martens, and Zelazny 1980)

and Parks 1980). Corn and soybeans were able to utilize appreciable amounts of subsoil K where the B horizon was within 50 cm depth. In these kinds of situations, crops may not give a response to K fertilization even though exchangeable K levels in the Ap horizon is low.

Sulfur

The S content of surface horizons of Oxisols and Ultisols is mostly in the organic form and the total amount is relatively low (Blair 1979). The total S content of the Ap horizon of Florida Ultisols averaged 66 $\mu g\ g^{-1}$ soil (Mitchell and Blue 1981). The surface horizons of most Ultisols and Oxisols contain low amounts of sulfate. The average sulfate concentration in the Ap horizon of southeastern U.S. soils was less than SO_4-S 10 $\mu g\ g^{-1}$ soil (Jordan 1964). The capacity of surface soils to adsorb sulfate is low and there is little buildup of sulfate in surface soils. Sulfate is readily leached from the Ap horizon and accumulates in the B horizon of Ultisols and Oxisols (Rhue and Kamprath 1973). Sulfates are adsorbed in the B horizon by the hydrated oxides of Fe and Al associated with the kaolinitic clays (Kamprath, Nelson, and Fitts 1956). These horizons are acidic and low in available P, which are conditions favoring adsorption of sulfate. Where Ultisols have been fertilized for a number of years with sulfur-containing fertilizers, there is appreciable accumulation of sulfate in the B horizon (Jordan 1964).

Responses to sulfur fertilization are dependent upon the amount of available sulfate in the Ap horizon, the depth to any sulfate accumulated in the B horizon, and the solubility of the adsorbed sulfate (Blair 1979, Fox 1980). Available sulfate in highly weathered soils has been estimated using a $Ca(H_2PO_4)$ solution containing 500 ppm P as the extracting solution. Critical levels for highly weathered soils have been estimated to be in the range of SO_4-S 4 to 10 $\mu g\ g^{-1}$ (Blair 1979). The critical level $Ca(H_2PO_4)$ extractable level in a Typic Paleudult was SO_4-S 6 $\mu g\ g^{-1}$ (Hue, Adams, and Evans 1984). When the 20 to 40 cm depth of Paleudults contained more than SO_4-S 7 $\mu g\ g^{-1}$, corn and soybeans did not respond to sulfur fertilization (Day and Parker 1982). Responses of corn and soybeans to sulfur fertilization were obtained when the Ap horizon of Hapludults was low in available sulfate and the depth to adsorbed sulfate was greater than 50 cm (Reneau and Hawkins 1980). Rates of SO_4-S 22 to 44 kg ha^{-1} gave maximum response of corn and soybeans.

Micronutrients

Low reserves of micronutrients are most likely on the highly leached, acid, coarse-textured soils. Zinc and boron are the micronutrients most often deficient. A survey of Paleudults in the middle coastal plain of South Carolina indicated an average available Zn level of 1.1 $\mu g\ g^{-1}$ soil (Segars and Woodruff 1972), which is above the critical level of 0.8 $\mu g\ g^{-1}$ for the double-acid extractant (Cox and Wear, 1977). Results of a regional study on Zn response of corn in the southeastern United States indicated mild zinc deficiencies may be found with corn. A survey of Cerrado soils in Brazil indicated that 81 percent of the soils were below the critical level for Zn (Lopes and Cox 1977). Yields of corn without Zn application were nil on a Typic Haplustox at Brasilia while maximum response was obtained with Zn at 3 to 9 kg ha^{-1} (North Carolina State University 1973). The 9 kg ha^{-1} rate also provided a residual effect for several years.

Boron deficiencies are most apt to occur on deep, coarse-textured soils and on soils recently limed to near neutrality. A survey of 15 sites in the middle coastal plain of South Carolina indicated that B concentrations of soybean leaves were in the sufficiency range (Segars and Woodruff 1972). Application of B to a Typic Haplustox in Brasilia did not increase corn yields (North Carolina State University 1973). Where soils are deficient, application rate of B 0.5 kg ha^{-1} is adequate for field crops.

Copper deficiencies have been reported on poorly drained, high organic matter soils and on coarse-textured mineral soils in the Atlantic coastal plain (Makarim and Cox 1983). Where double-acid Cu soil test levels were low (less than Cu 0.3 $\mu g\ g^{-1}$), wheat responded to application of Cu 2 kg ha^{-1} on mineral soils. Extractable Cu in Cerrado soils of Brazil was low, but few Cu deficiencies have been reported (Lopes and Cox 1977).

Manganese deficiencies can be induced when soils are limed excessively. Lime rates to neutralize exchangeable Al will not induce Mn deficiencies.

Molybdenum deficiencies are common on acid, highly weathered soils. When soils are limed, Mo deficiencies are generally corrected (Adam 1978).

Nitrogen

Low activity clay soils generally have low amounts of organic matter and supply only small quantities of N by mineralization of organic nitrogen. Nitrogen fertilization must be based on the requirement of the crop being grown. Because nitrate is a highly mobile anion, nitrogen fertilizers should

be applied at times in split applications. Only small amounts of N should be applied at planting and the remainder when the plant starts to make its rapid growth. If soils are subject to leaching, the side-dressing application of N may be split into several applications.

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MANAGEMENT OF LOW ACTIVITY CLAY SOILS WITH SPECIAL REFERENCE TO ALFISOLS, ULTISOLS, AND OXISOLS IN THE TROPICS

B.T. Kang[1] and J.M. Spain[2]

Introduction

World population, currently estimated at more than 4.3 billion, has increased at a rate of 1.8 percent per year during the last decade. Wortman and Cummings (1978) projected a doubling of population in 38 years if this rate continues. As growth rates vary from continent to continent, greater concern has been expressed in recent years as to the ability of areas with high population density and growth rates to feed their increasing population. A case in point is the African continent, where the average annual population growth during the 1970s was 2.6 percent, greatly exceeding the annual increase in food production of 1.3 percent (Dudal 1980). Dudal estimated that agricultural production must increase by 60 percent by the year 2000 in order to meet future world food requirements.

It is obvious that increased food production in the future must come from intensification of agriculture, especially in developing countries and/or from the expansion of frontiers to include new land, mainly in the tropics (Bentley 1979, Dudal 1980, Sanchez and Cochrane 1980). Vast areas, some of which are suitable for agricultural expansion in the humid forest and savanna regions of the tropics, are dominated by low activity clay (LAC) Alfisols, Ultisols, and Oxisols (Kellogg and Orvedal 1969, NAP 1977, Sanchez and Cochrane 1980).

The relatively more fertile Alfisols and related soils which cover about 4 percent of the humid tropics and 33 percent of the semiarid tropics (Table 1), already support rather dense populations, while the acid and infertile Ultisols, which cover 28 percent of the humid tropics, support lower population densities but are currently also being rapidly developed. The Oxisols account for an estimated 35 percent of the humid tropics but are very sparsely populated.

To meet the goal of increased food production in areas dominated by LAC Alfisols, Ultisol, Oxisols, where shifting cultivation and related bush and grass fallow-land rotation systems are still widely practiced, it is essential that appropriate soil management technology be used. The question is whether such technology is presently available.

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[1] Soil Scientist, IITA, Oyo Road, Ibadan, Nigeria.
[2] Soil Scientist, CIAT, Cali, Colombia.

Table 1. Geographical distribution of soils in the humid and semiarid tropics (millions of hectares).

Soil Order	Tropical Asia	Tropical Africa	Tropical America	Total	Percent
Humid Tropics*					
Oxisols	14	179	332	525	35
Ultisols	131	69	213	413	28
Inceptisols	90	75	61	226	15
Entisols	90	91	31	212	14
Alfisols	15	21	18	54	4
Others	39	10	11	60	4
Total	379	445	666	1490	100
Semiarid Tropics†					
Alfisols	121	466	107	694	33
Aridisols	47	440	33	520	25
Entisols	--	255	17	272	13
Inceptisols	28	38	--	66	3
Ultisols	20	24	8	52	1
Others	103	239	148	490	25
Total	319	1462	313	2094	100

* Data from NAS (1982).
† Data adapted from Kampen and Burford (1980) covered also part of subhumid tropics.

In this paper, the authors do not attempt to make an exhaustive review of published information on the management of LAC Alfisols, Ultisols, and Oxisols, but instead highlight some of the more recent findings of soil management research focused on increased food, forage, and tree crop production on these soils.

Land Use and Farming Systems

According to calculations made by Sanchez (1976), approximately 10 percent of the total land area in the tropics is cultivated. Pastures and meadows

account for an additional 20 percent. Tropical Asia has the largest proportion of cropland (27 percent) followed by tropical Africa (8 percent) and tropical America (6 percent). Tropical Africa has the largest proportion of permanent pasture (30 percent), followed by tropical America (22 percent) and tropical Asia (2 percent). No published data are available on specific land use on LAC soils in the tropics.

Shifting cultivation and related bush and grass fallow rotations are still the dominant farming systems in the tropics. They cover over 30 percent (360 x 10^6 ha) of the exploitable area (FAO/SIDA 1974). For tropical Africa, Greenland (1974) distinguished four phases of shifting cultivation and land rotation systems. These were further elaborated by Moormann and Greenland (1980), showing the relationship between land categories and soil orders (Table 2). Cropping intensity is greater on the high base status and deep Alfisols than on the Ultisols and Oxisols. Cereals and legumes are the dominant crops on the Alfisols. In the humid and subhumid regions of Africa, upland rice, maize, soybeans, cowpeas, yam, and cassava are widely grown in intercropped systems. A wide range of crops is also grown on Alfisols in the semiarid tropics of Asia and Africa (Jones and Wild 1975, Kampen and Burford 1980). The main crops are millet, sorghum, groundnut, cowpea, chickpea, pigeon pea, cotton and, to a lesser extent, maize and cassava. These crops are grown either in monoculture or intercropped, depending on climate. Root and tuber crops (cassava, yam, cocoyam), rice, banana, and plantains are the dominant crops grown in multiple cropping on the acid Ultisols and Oxisols.

Sanchez and Cochrane (1980) listed nine major agricultural production systems on Alfisols and five major agricultural production systems on Ultisols and Oxisols in tropical America. On the Alfisols, a wide variety of crops including sorghum, maize, cowpea, soybean, cassava, other root crops, cotton, banana, cocoa, and pastures are grown in the lowland tropics and maize, beans, plantain, coffee, and pastures in the highlands. Production systems on the Ultisols and Oxisols include (1) shifting cultivation in the forest regions of the Amazon with maize, cassava, and rice as the most commonly grown food crops; (2) extensive cattle grazing practiced in the savannas of Colombia, Venezuela, and Bolivia; (3) crop-cattle grazing systems practiced in the Cerrado of Brazil involving rotation of rice, sorghum, peanuts, and pastures; (4) intensive production of soybeans and rice in the Minas Gerais area of Brazil; and (5) intensive coffee and sugarcane plantations in south-central Brazil.

The most stable, usually capital intensive, and most intensively researched production systems in LAC soils in the tropics are perennial

Table 2. Phases of shifting cultivation and tentative relationships with land categories and soil Orders (Moormann and Greenland 1980).

	Phase I	Phase II		Phase III	Phase IV
Phases of land cultivation	Simple shifting cultivation Dwellings and cultivated area shift together	Recurrent cultivation May be complex, with several fields		Recurrent cultivation with continuously cultivated plots Always complex, with several field types	Continuous cultivation May involve alternate husbandry with planted and cultivated pastures and fallow crops
Land categories	Shifting cultivation L* > 10	Recurrent Cultivation Land			Permanent (L < 2) and semipermanent land use L < 2 - 3
		Long-term recurrent cultivation L = 7 - 10	Medium-term recurrent cultivation L = 5 - 7	Short-term recurrent cultivation L = 3 - 5	
Principal soil Order of association (tentative)	Any	Alfisols Ultisols Ultisols	Alfisols Deeper Ultisols	Alfisols Deeper Ultisols	Alfisols Andepts

* L = Land Use Factor, defined as $L = \frac{C + F}{C}$ where C = length of cropping period in years,
F = length of fallow period in years.

plantation crops: cocoa, oil palm, rubber, tea, coffee, banana (Smyth 1966, Ng 1972, De Geus 1973, Chan 1979).

Distribution of LAC Soils

Oxisols are the most abundant soils in the humid tropics covering an estimated 35 percent of the land area (Table 1). Ultisols are the second most abundant, covering an estimated 28 percent of the region. About half of the Ultisols and 60 percent of the Oxisols are located in humid tropical America. They are the dominant soils in the Amazon and Orinoco basins and in the Atlantic coast of central America and humid coastal Brazil (NAP 1982).

Ultisols and Oxisols are the most abundant soils in humid tropical Asia, occupying most of Malaysia, Sumatra, Kalimantan, Sulawesi, and Mindanao (Dent 1980, NAP 1982). They also cover considerable areas of humid tropical Africa (Dudal 1980). They are abundant in the eastern Congo basin bordering the lake region, in the forested zones of Sierra Leone, in Ivory coast, in parts of Liberia, and in the forested coastal strip from Ivory Coast to Cameroon.

The Alfisols which have high to moderate fertility, cover a smaller area of the humid tropics. They occur in spots in the Amazon basin, near Altamira, Porto Velho, and Rio Branco in Brazil; in parts of the high selva in Peru; on the humid coast of Ecuador; and on the southern coast of Bahia in Brazil. In Asia, they are found in the Philippines and Java, and in West Africa they are found in Ivory Coast, Ghana, Togo, Benin, Nigeria, and Cameroon (NAP 1982).

Alfisols are the most abundant soils in the subhumid and semiarid zones, covering about one third of the region. They are most widely distributed in the subhumid and semiarid tropics regions of Africa including large areas in western, eastern, central, and southeastern Africa. In Asia, they are most abundant in the Indian subcontinent, in Sri Lanka, Thailand, and Kampuchea. They also cover large areas in northeastern Brazil and are found in Bolivia, Colombia, and Mexico (Aubert and Tavernier 1972).

Constraints for Food Production

Enormous areas covered by LAC soils in the tropics are currently used for traditional shifting cultivation and related bush and grass fallow systems or &not used at all. As most of these areas are located in thinly populated regions, they have received much attention in recent years as potential areas for agricultural intensification and expansion to meet future food requirements. Dudal (1980) estimated the need for expansion of agricultural

lands to be as much as 200 million ha in the tropics before the end of the century. For Africa, an additional 31 million ha would need to be taken into cultivation by 1990. The largest potential for expanding agriculture lies in tropical America where 700 million ha of forested land and 300 million ha of savanna are considered usable (NAS 1977). However, Alfisols, Ultisols, and Oxisols, characterized by low activity clays and low cation-exchange capacity (Uehara 1978) in the humid, subhumid and semiarid regions of the tropics, are known to have serious physical and chemical constraints for development of efficient crop production systems (IRRI 1980).

Sanchez and Cochrane (1980) in reviewing the constraints and management problems of LAC soils in humid and subhumid tropical America compiled a long list of constraints. The following are some of the main problems: The productivity of high base status Alfisols with moderate to high fertility status is mainly limited by physical conditions, including susceptibility to erosion, low water-holding capacity, and drought stress. However, deficiencies of N and P are widespread and deficiencies of S, Fe, and Zn are found in localized areas. In contrast, the major constraints of the low base status Ultisols and Oxisols are chemical in nature. Although P is generally a limiting element, deficiencies of N, K, S, Ca, Mg, and Zn are common. These soils have high to moderate P fixation capacities (Juo and Fox 1977, Sanchez and Uehara 1980). In addition, aluminum toxicity is almost universal, and manganese toxicity is often limiting, especially in Ultisols. The Ultisols are especially susceptible to erosion and soil compaction.

In humid tropical Asia (Dent 1980), the Ultisols and Oxisols have acidity problems with low inherent fertility, and the Ultisols are subject to erosion, particularly on exposed slopes. The Alfisols, which have moderate to high agricultural potential, are highly susceptible to erosion and moisture stress.

The Alfisols, Ultisols, and Oxisols in humid and subhumid tropical Africa have major constraints (Lal 1979, Moormann and Greenland 1980, Kang and Juo 1981). The Alfisols are extremely susceptible to soil erosion and soil compaction and have low water retention, and, thus, are subject to drought (Lal 1976, Lal 1979, Kang and Juo 1981). Deficiencies of N and P are common, while localized deficiencies of K, Mg, Fe, Zn, and S occur under intensive cultivation (Kang and Fox 1981, Cottenie _et al_. 1981). The Alfisols also acidify rapidly under continuous cultivation (Kang and Juo 1981). The Ultisols and Oxisols have problems associated with acidity and Al toxicity. Although P deficiency is widespread, the soils have only moderate P fixing capacity (Juo

and Fox 1977). Low nutrient reserves, nutrient imbalance, and multiple nutrient deficiencies (N, P, K, Ca, Mg, and Zn) are common problems (Juo and Uzu 1977, Kang and Juo 1981).

The constraints of Alfisols in the African and Asian semiarid tropics have been discussed in numerous publications (Charreau 1974, Jones and Wild 1975, Kampen and Burford 1980). The semiarid tropics Alfisols also suffer from major physical limitations. They are moderately suited for intensive cropping, but suffer from crusting, compaction, erosion, low moisture retention, and drought stress (Poulain and Tourte 1970, Charreau and Nicou 1971, Jones and Wild 1975, Kampen and Burford 1980). Most African semiarid tropics Alfisols have low fertility (Jones and Wild 1975) and are universally deficient in N and P. Potassium deficiency is becoming a problem in many areas under continuous cultivation (Jones and Wild 1975, Kampen and Burford 1980). Localized deficiencies of S, Zn, and B are also common in Africa (Kang et al. 1981, Cottenie et al. 1981).

Management of LAC Soils

Traditional Methods of Soil Management

In areas where shifting cultivation and related fallow systems are dominant, traditional farmers rely on forest or savanna fallow for restoring the fertility exhausted during the cropping cycle. Deep-rooting trees, shrubs, and grasses in the fallow play a very important role in recycling plant nutrients from lower soil horizons and accumulating them in the biomass. Though traditional burning of the biomass following clearing is seldom complete, it assists in the release of nutrients for subsequent crops. The effect of burning on soil fertility is influenced by type and age of fallow vegetation and soil type. The data included in Table 3 from southern Nigeria show that the effect of plant ash on soil chemical properties is generally more pronounced on the low base status and acid Ultisols than on high base status Alfisols. The effect of burning on soil fertility, particularly on the acid Ultisols, is of short duration; on the order of one to two crops according to Seubert, Sanchez, and Valverde (1977) and Okoro (1981).

The natural fallow systems practiced in humid tropical Africa have evolved through centuries of trial and error into ecologically sound ways of managing soils and other agricultural resources. Indigenous tribes in Central and South America developed and used similar systems. These traditional systems are different from the destructive slash-and-burn methods practiced mainly by new

Table 3. The effect of burning plant residue following land clearing, on the chemical composition of the surface layer (0 to 7.5 cm) of an Alfisol and an Ultisol (Kang and Juo 1982).

Treatment	pH (H_2O)	Organic C (%)	Exchange cations, meq/100g Ca	Mg	K	Al	Extractable P (Bray 1) ppm
Ultisols (Typic Paleudult) Onne, Nigeria							
BB*	4.3	1.73	1.32	0.34	0.16	1.44	108
AB†	5.0	1.82	2.96	0.85	0.33	0.08	123
Alfisol (Oxic Paleustalf) Ibadan, Nigeria							
BB	6.0	1.58	5.87	1.57	0.33	--	4.7
AB	6.3	1.37	7.48	1.94	0.97	--	20.7
LSD .05	0.1	0.24	1.24	0.26	0.18	--	2.6

* BB = Before burning.
† AB = After burning.

settlers on steep, high jungle lands in South America (Watters 1971). Where land is abundant enough to allow long fallow periods, the traditional natural fallow rotation systems are quite stable, though of low productivity, suitable primarily for subsistence agriculture (Moormann and Greenland 1980).

One main disadvantage of this type of soil fertility regeneration is the large area of land required per individual inhabitant. Rapid population growth and migration in tropical Africa and other tropical regions has placed considerable pressure on the system, forcing a drastic shortening of the fallow period. In some areas of humid West Africa, five or more fallow years are required before crops can be successfully cultivated again (Nye and Greenland 1960). Farmers in the humid region of southern Nigeria have recognized the ability of certain species, such as *Anthonata mycrophylla*, *Alchornea cordifolia*, and *Acioa barterii*, to rapidly regenerate soil fertility in short fallow cycles and have retained them in the natural fallow (Getahun, Wilson, and Kang 1982). However, in most areas, shorter fallow cycles do not allow enough fertility regeneration for sustained agricultural productivity and

result in soil degradation and declining yields (Ruthenberg 1976). The rates of fertility and yield decline vary considerably depending on the nature of the soils. The decline may be less rapid for Alfisols than for Ultisols and Oxisols (Sanchez 1976). The decline in nutrient status is also faster with poor crop husbandry. The effect of increased weed competition is more pronounced under low fertility (Kang, Donkoh, and Moody 1977).

Alternative soil management technologies which are more stable and efficient are needed, particularly for small farmers holder in most of the tropics dominated by LAC soils. The goal should be to increase sustainable food production while conserving the resource base.

Alternative Methods of Soil Management

Repeated attempts to replace ecologically stable bush-fallow subsistence food crop production systems with "modern agriculture" based on intensive mechanization and the use of agrochemicals have consistently produced discouraging results on the LAC soils in tropical Africa (Moormann and Greenland 1980). The arbitrary application of exotic, high input, food crop production technologies to such fragile soils often leads to rapid chemical, physical, and biological degradation of the soil.

Results of investigations carried out during the last two decades at various tropical research centers have provided a better understanding of how to manage LAC soils, and serve as a basis for the development of technologies that will allow extended periods of cropping of these soils without excessive use of purchased inputs (Lal 1974; Spain _et al_. 1975; Kang and Juo 1981; Spain 1981_b_; IITA 1981; Goedert, Lobato, and Resendse 1982; Kampen and Burford 1980; Sanchez and Salinas 1981; Uehara 1982; Nicholaides _et al_. 1984).

Effect of Land-clearing Methods

The choice of appropriate land-clearing methods, the first step in crop production, is very important. Clearing can result in either sustained long-term productivity, the need for expensive remedial measures at later stages, or irreversible damage to soils. The effect of land-clearing depends largely upon soil type, rainfall regime, and soil moisture status at the time of clearing. Seubert, Sanchez, and Valverde (1977) reported significant differences in soil chemical properties of a strongly acidic Ultisol and Yurimaquas due to manual clearing followed by burning compared with bulldozer clearing without burning. The latter method caused considerable soil

disturbance and resulted in poorer crop performance as compared to the slash-and-burn clearing system. Kang and Juo (1982) observed small differences in chemical properties of a less leached but rather heterogeneous Alfisol following manual and mechanical clearing. Manual and shear-blade cleared sites had better nutrient status than those cleared with tree pusher/root rake. On Alfisols, crop yields are reported to be better on manually cleared land (Lal 1981) from shear-blade rather than tree pusher/root rake attachments (Couper, Lal, and Claassen 1981). Manual operations also result in less drastic alteration of physical properties of Ultisols (Seubert, Sanchez, and Valverde 1977) and Alfisols (Lal and Cummings 1979). Observations on an Ultisol in southern Nigeria also indicate that less time is needed with the slash-and-burn method of land clearing. Where labor is available, manual land clearing is almost always preferable on these soils.

Management of Alfisols for Continuous Cropping

Significant changes in soil chemical and biological properties occur in West African Alfisols under cropping following land clearing. Soil organic matter declines sharply during the first few years under cropping (Cunningham 1963, Adepetu and Correy 1979). Continuous cropping also results in a sharp decline in pH, and the effect is more pronounced when moderate to heavy rates of acidifying fertilizers are used (Table 4). This loss of organic matter and acidification resulted in a decrease in the effective cation-exchange capacity (ECEC) and the loss of exchangeable Ca and Mg (Kang and Juo 1982). It thus appears that even on relatively high base status Alfisols, lime will be needed after a few years of annual cropping.

Crop residue management and tillage methods can play a very important role in maintaining the organic matter in these soils (Lal and Kang 1982). Retention of maize residue as mulch has maintained high organic matter levels in long-term fertility plots in southern Nigeria (Kang and Juo 1982). Similarly, planted fallows (Panicum maximum and Leucaena leucocephala) can maintain high organic matter levels (Juo and Lal 1977). One of the major problems associated with extended cultivation of these soils is the maintenance of favorable soil physical conditions and the control of soil erosion (Wilkinson 1975, Lal 1979). This can be done through the use of crop residue mulches and in situ mulches from cover crops (such and Mucuna utilis) in reduced tillage systems. The presence of a mulch cover helps maintain high soil nutrient status and high biological activity, and also protects the soil

Table 4. Changes in surface soil acidity in a kaolinitic Alfisol (Oxic Paleustalf) under continuous cropping, Southern Nigeria

	Number of crops					
Treatment	0	1	2	3	4	5
	pH, 0.01M $CaCl_2$					
Control	5.80	5.65	5.82	5.50	5.55	5.60
NPK*	5.80	5.15	5.35	5.36	5.06	5.13

* Total N applied = 520 kg ha; 120 kg as ammonium sulphate was applied to first crop, after which urea was used.

against excessively high temperatures, soil erosion, and runoff, preventing the breakdown of soil structure and the resultant soil compaction and decreased permeability, and increasing soil moisture retention (Lal 1974, Spain 1983, Spain and Salinas 1984).

Field experiments conducted on Alfisols in southern Nigeria show that with judicious fertilizer use and improved crop varieties high yields can be maintained (Kang and Juo 1982). The important components of a successful continuous cropping system included: crop rotation, fertilizer application, and retention of crop residues. In a trial initiated in 1972 on a kaolinitic Alfisol derived from banded gneiss, with moderate fertilizer rates (Table 5), the main season maize yields have been sustained at over 4.5 tons/ha during 12 years of cropping (Figure 1), and the yield of the minor season cowpea (relay cropped), with only residual fertilizer from the preceding maize crop, was sustained at about 1 ton/ha.

On generally, highly erosive Alfisols, no-tillage production systems with crop residue mulching on newly cleared forest land have been shown to have distinct advantages (Lal 1974; Couper, Lal, and Claassen 1981) Maize yields were higher with no-tillage than with traditional plowing for 24 consecutive crops on an Alfisol (IITA 1983).

Experiments conducted over a 6-year period on a kaolinitic Alfisol at IITA, Ibadan, have shown that mechanized, continuous no-till maize production is possible on slopes of up to 15 percent without serious erosion. Maize

Table 5. Estimated annual fertilizer requirement for main season maize crops grown on an Alfisol (Oxic Paleustalf) derived from banded gneiss following hand clearing and removal of debris from secondary forest at Ibadan, Nigeria.

Input	Response	Rate (ha/crop)
Nitrogen	Second to 10th	90-120 kg N
Phosphorus	First to 3rd year	60 kg P
	Fourth to 10th year	30 kg P
Potassium	Ninth to 10th year	80 kg K

NOTE: No responses to applied S, Mg, and Zn during trial period. Crop residue retained in plots. Maize followed by minor season sweet potato during first 4 years, then by cowpeas.

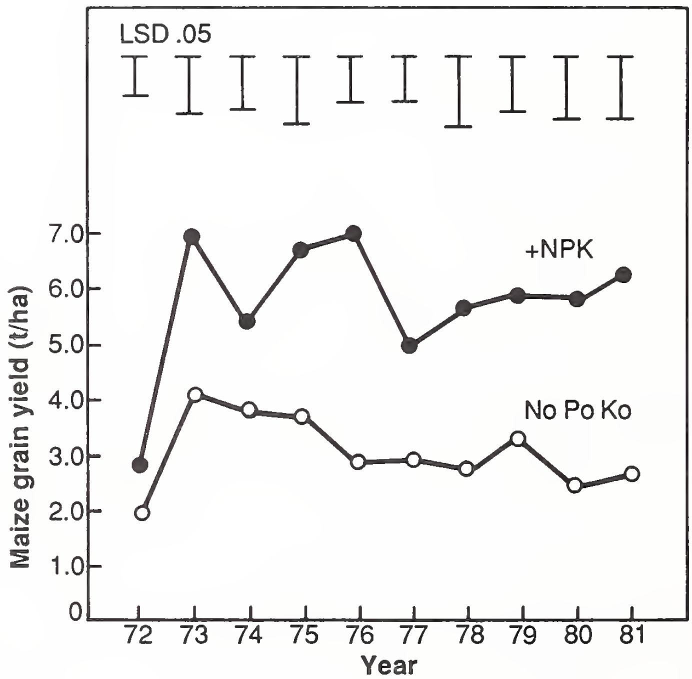

Figure 1. Main season grain yield of maize (cv TZPB) grown in rotation with sweet potato and cowpea on a kaolinitic Alfisol (Paleustalf) with and without fertilizer on land cleared from secondary forest (Kang and Juo 1982).

yields from no-till, residue mulch systems were consistently higher than those from conventional tillage treatments, but because of a variety of factors, including soil compaction and acidification, yields declined after 8 successive crops (Hartmans 1981). These results show one of the inherent limitations to the use of the highly erosive, kaolinitic LAC Alfisols for continuous mechanized food crop production. There is a need for testing alternative tillage and inclusion of planted fallows in production systems on this soil to overcome soil compaction problems. ICRISAT has developed a broad bed-and-furrow system for semiarid tropics Alfisols which provides better soil and water conservation and higher crop yields than has been possible with traditional systems (Kampen and Burford 1981). The tied-ridge system has also been used successfully for soil and water conservation (Lawes 1963). Recent research results of Rodriguez (IITA 1983) in Burkina Faso also show the importance of tied ridges in reducing drought risk in maize. Pichot et al. (1981) report that the addition of organic residues and fertilization are important in maintaining crop yields on semiarid tropics Alfisols under continuous cropping.

Management of Ultisols for Continuous Cropping

Soil management systems suitable for continuous crop production on many Ultisols have been developed independently by several research institutions working in the humid tropics in recent years (McIntosh et al. 1981, IITA 1981, Nicholaides et al. 1984). The resulting technology is considered to be applicable for large areas in the humid tropics.

Juo (IITA 1981) recently summarized the technology developed by IITA for managing the coarse-textured kaolinitic Ultisols (Typic Paleudults) for sustained crop production. Maize and cowpea yields can be maintained over a period of seven years on small farms with low rates of lime (200-400 kg/ha/yr) in combination with applications of 120-50-30-10-5 kg/ha N-P-K-Mg-Zn applied to the first season maize crop. The cowpea crop planted in the second season receives no fertilizer. Lime is considered a fertilizer rather than a soil amendment.

The Tropical Soils Research Program of North Carolina State University (NSCU) and the National Institute of Agricultural Research and Promotion in Peru (INIPA) have carried out a large number of investigations at Yurimaguas, Peru, in order to develop soil management technologies that will enable continuous cropping on the acid, infertile low and high activity clay Ultisols

in the region. Important components of the technology as summarized by Nicholaides et al. (1984) include choice of crops, rotations, and fertilizer to provide adequate nutrients as determined by soil testing. These authors summarized lime and fertilizer requirements, as shown in Table 6, to achieve and sustain moderately high yields of an upland rice-groundnut-soybean rotation of over 2.0 t/ha for each of the crops. Although liming has a beneficial effect on the yields of most crops, more work remains to be done in defining specific lime requirements, based on crop characteristics, soil conditions, and farming systems used (Goedert, Lobato, and Resendse 1984).

Results of various trials conducted on fragile Ultisols in the central Lampung area of the Island of Sumatra, Indonesia, show good potential of these soils for production of selected crops with proper soil management (Manuelpillai et al. 1980, McIntosh et al. 1981). Maize yields of 5 to 6 tons/ha were obtained with initial applications of 80 kg N, 80-120 kg P, 50 kg K, 50 kg Mg, and 1000 kg lime/ha and applications of B and Zn as needed (Manuelpillai et al. 1980). McIntosh et al. (1981) were also able to maintain relatively high yields of maize, upland rice, rice-beans, peanuts, and cassava for 5 years with annual applications of 125 kg N and 100 kg P/ha and one application of one t/ha of burned limestone during the 5 years. Fertilizers should be put as close as possible to the root zone. The authors also emphasize the need for retaining crop residues to maintain soil organic matter, better buffering, and exchange capacity of these soils. Soil productivity can be maximized by mulching and intercropping to provide continuous soil coverage.

Soil Management Technologies for Low Cost and Extensive Crop Production on LAC Ultisols and Oxisols

Some progress has been made in developing low-cost technology based on selecting plants adapted to acid, infertile soil conditions rather than eliminating stresses by heavy use of lime and fertilizers (Spain et al. 1975, Spain 1981b). The most promising strategies for acid Ultisols and Oxisols involve the use of permanent legume-based pastures or upland rice-pasture systems.

Pastures can play a special role in the development of these soils in frontier areas for a number of reasons as outlined by Spain (1981a):

- Many high quality, potentially productive tropical forage species are well adapted to the edaphic environment with minimum fertilizer requirement, having evolved in acid infertile soils (Spain 1979). A few species

Table 6. Lime and fertilizer requirements for continuous cropping of a three crop per year rotation in an Ultisol at Yurimaguas, Peru (Nicholaides 1984).

Input*	Rate per hectare	Frequency
Lime	3 tons $CaCO_3$-equivalent	Once per 3 years
Nitrogen	80-100 kg N	Rice and maize only
Phosphorus	25 kg P	Each crop, split applied
Potassium	160 kg K†	Each crop, split applied
Magnesium	25 kg Mg	Each crop, unless dolomitic lime is used
Copper	1 kg Cu	Once/year or two years‡
Zinc	1 kg Zn	Once/year or two years‡
Boron	1 kg	Once/year or two years‡
Molybdenum	20 g Mo	Mixing with legume seed during inoculation

* Calcium and sulphur requirements are satisfied by lime, single superphosphate, and Mg, Cu, and Zn carriers.
† Potassium rate may increase depending on soil test.
‡ Depends on soil test.

combine these qualities with sufficient disease and insect resistance to persist under grazing in stable associations.

- Well-managed perennial pastures comprising of acid soil tolerant, deep-rooting legumes and grasses conserve the soil resource, protecting it from erosion and efficiently recycling nutrients from the subsoil to the surface.
- Well-adapted legumes are capable of supplying the N requirements of associated grasses for productive, high quality pastures.
- Perennial C-4 tropical grass species are among the most efficient converters of solar energy.
- The above characteristics make it possible to achieve relatively high output from low-input (purchased) systems.

- Pasture-based livestock systems often catalyze the development process in frontier areas by generating capital and stimulating the development of infrastructure; this, in turn, leads to more intensive land use and increased production.

The production potential of legume-grass associations on LAC soils has been amply demonstrated in the Llanos of Colombia. In Table 7, a summary of research results from 1970 to 1981 in Carimagua illustrates the dramatic increase in production potential as one moves from native savanna to improved grasses and finally to grass-legume associations (CIAT 1981). Productivity of pure grass stands in terms of live weight gain/ha/year is surprisingly high for pastures that receive no nitrogen fertilizer. However, the gain/animal/year is still rather low compared to the gains achieved with animals grazing on grass-legume associations. This is of special importance where pastures are to be used primarily in cow-calf operations, where one of the major objectives is to provide pasture of sufficiently high quality so that the lactating cow maintains or improves body condition and conceives within 3-4 months of calving.

Recommended fertilizer rates for pasture establishment in the Colombian Llanos are 22, 24, 50, 12 and 12 kg/ha of P, K, Ca, Mg and S, respectively. Maintenance rates tentatively recommended are 5, 10, 12, 8, 8 kg/ha/yr.

In the Brazilian Amazon basin, a gradual decline in the yields of straight grass pastures occurs, mainly due to P deficiency according to Serrao et al. (1979). They recommend periodic applications of phosphorus and inclusion of legumes such as Pueraria phaseoloides, Desmodium ovalifolium, and Stylosanthes guyanus in pastures to maintain their productivity.

In the upland rice pasture system widely practiced in the Brazilian Campo Cerrado (Goedert, Lobato, and Lesendse 1982), the farmer ploughs the land after clearing trees and shrubs and grows upland rice for 2 to 3 years, usually without liming and with fertilizer applied to the rice at low rates, mainly phosphorus at 22-44 P kg/ha. When fertility declines and/or weeds become a problem, the farmer changes to pasture, usually Bracharia decumbens but more recently including Andropogon gayanus. These pastures when well-managed will last several years, with much higher productivity than native Cerrado pastures.

Low Input Soil Management Involving Trees and Shrubs

The integration of food crops and forages with tree crop production in agroforestry systems has received more attention in recent years as an

Table 7. Pasture productivity in terms of live weight gains, and a summary of evaluations at Carimagua, 1970-1981 (Spain 1981a).

Type of pasture	Average live weight gains			
	Dry season	Wet season	----- Total for year------	
	----- g/animal/day -----		kg animal^{-1}	kg ha^{-1}
Managed savanna*	-167	449	90	22
Grass Pastures				
*Melinus minutiflora**	-445	508	97	43
*Brachiaria decumbens**	180	443	131	282
Andropogon gayanus†	- 44	480	110	350
Associations†				
A. gayanus x Stylosanthes capitata	187	707	183	345
A. gayanus x Pueraria phaseoloides	390	693	203	364
Protein Banks‡				
B. decombens x P. phaseoloides in blocks	350	535	159	293
B. decumbens x P. phaseoloides in strips	484	577	185	299
Savanna + Protein Bank (2000 m^2 leg animal^{-1})				
Savanna (0.25 animals ha^{-1}) + *P. phaseoloides*	145	457	123	31
Savanna (0.50 animals ha^{-1}) + *P. phaseoloides*	63	388	102	51

* More than 3 years.
† Average of last 2 years.
‡ Average of 3 years.

alternative low input management possibility for LAC soils. Integration of limited food production at the initial stage of forest regeneration in what is known as the _taungya_ system has been successfully practiced on LAC soils with no purchased inputs required.

Traditional bush fallow rotation systems rely on trees and shrubs for nutrient recycling and soil fertility regeneration. In an effort to make this system more productive, the IITA has developed an alley cropping system (Kang, Wilson, and Sipkens 1981). This is a form of agroforestry where annual crops, including food crops, are grown in the alleys between hedgerows of planted shrubs and trees. The hedgerows are periodically pruned during the cropping season to prevent shading and provide mulch and green manure for the companion crop. Leguminous trees and shrubs such as _Leucaena leucocephala_ and _Gliricidia sepium_ contribute biologically fixed nitrogen to the system. Results of seven years of observations in southern Nigeria indicate that this system can be used successfully for sustained food crop production on high base status Alfisols and related soils with low (purchased) input requirements (Kang, Wilson, and Lawson 1984).

The use of fertilizers in improved farming systems results in the removal of large amounts of nutrients in crops, thus will require a corresponding increase in the return of bases for acidity correction to maintain high levels of production on LAC soils. In many parts of the humid tropics where lime is not readily available, the inclusion of trees and shrubs in the crop production system as practiced in alley cropping can serve as an important solution to the acidity problem. Deep-rooting trees and shrubs are able to absorb cations leached from the surface and return them to the topsoil through leaf litter or prunings.

There has been increased interest in recent years in developing agro-silvopastoral systems as low input soil management systems for LAC soils (Bishop 1982, Sumberg 1984). Certain woody perennials favor pastures growing underneath mainly through soil enrichment (Torres 1983).

Multistory cropping in compound farming, also known as village forest gardens, which may involve a wide variety of food and tree crop species (Michon 1983), is widely practiced by traditional farmers on LAC soils with very low inputs. This is a well-balanced soil management system that has been practiced by farmers for centuries. Though very successful, it is little researched, mainly due to its complexity.

Management of LAC Soils for Perennial Crop Production

Soil management requirements for production of perennial crops such as rubber, oil palm, cocoa, and bananas on LAC soils have been intensively researched. Sustained, high yield production of rubber and oil palm on Ultisols and Oxisols in southeast Asia and Africa is well documented (Ng 1972, Chan 1979). Cocoa is more sensitive to acidity and is usually grown on the more fertile Alfisols in the humid tropics (Smyth 1966). The management requirements of these soils for successful production of perennial crops is well known and includes use of cover crops and less fertilizer than required for annual food crops, mainly as a result of: (1) less extraction of nutrients with the harvest; (2) nutrient recycling by the perennial trees; and (3) the nutrient contribution of cover crops, mainly N.

Crops such as coffee and tea, which are tolerant of acid soils, are also grown on Ultisols and Oxisols, usually at high elevations. These crops require intensive fertilization (De Geus 1973).

Summary and Conclusions

LAC Oxisols, Ultisols, and Alfisols make up a large portion of the land area in the tropics. In the humid tropics, Oxisols occupy 35 percent of the land area, followed by Ultisols with 28 percent, and Alfisols with only 4 percent. In the subhumid and semiarid tropics, LAC Alfisols cover 33 percent of the area and are more important than LAC Ultisols. Large areas of LAC soils as yet undeveloped have potential for increasing food production with proper soil management techniques.

Shifting cultivation and related bush and grass fallows are still the dominant land-use systems on these soils, particularly in tropical Africa. The high base status LAC Alfisols, which are used very intensively, also produce a wide range of food crops, including cereals, legumes, and root and tuber crops. The low base status and acid Ultisols and Oxisols are dominated by root and tuber crops and extensive grazing areas in tropical America. Most of these crops are grown in multiple cropping systems. Plantations of perennial trees are the most stable farming systems for LAC soils.

Alfisols, Ultisols, and Oxisols have major limitations for developing more intensive crop production systems. Alfisols have major physical limitations including low moisture holding capacity and low structural stability, thus are susceptible to erosion, crusting, and soil compaction; drought stress is a

major problem in the semiarid tropics. Nutrient deficiencies and soil acidification with cropping can become serious problems. Ultisols and Oxisols have major chemical constraints: extreme acidity, Al toxicity, multiple nutrient deficiencies, and nutrient imbalances are major problems. Soil erosion and compaction can also be problems, especially on Ultisols.

A number of promising soil management technologies have been developed by various research institutions in recent years that provide possibilities for more intensive utilization of these LAC soils for sustained crop production. Central ingredients to these technologies are (a) the need for appropriate land clearing and post land-clearing management techniques; (b) provisions for better ground cover either by crops, pastures, or mulch; (c) reduced tillage; (d) judicious fertilizer and lime use; (e) the use of crops which are adapted to the chemical edaphic environments, and (6) inclusion of woody leguminous species in continuous production systems.

Despite the progress made in developing technologies for managing LAC soils, there is urgent need for more research, particularly to better manage the vast areas of LAC Ultisols and Oxisols that are rapidly being cleared for annual crop production and perennial pastures.

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